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CANADIAN THESES ON MICROFICHE

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TITLE OF THESIS/*TITRE DE LA THÈSE* The Effects of Some Physical Factors on Dust Concentrations in a Pig Barn

UNIVERSITY/*UNIVERSITÉ* University of Alberta, Edmonton

DEGREE FOR WHICH THESIS WAS PRESENTED/ *GRADE POUR LEQUEL CETTE THÈSE FUT PRÉSENTÉE* M.Sc.

YEAR THIS DEGREE CONFERRED/*ANNÉE D'OBTENTION DE CE GRADE* 1975

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THE UNIVERSITY OF ALBERTA

THE EFFECTS OF SOME PHYSICAL FACTORS ON DUST CONCENTRATIONS IN A PIG BARN

by

© LAURENCE FRANK HONEY

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

DEPARTMENT OF AGRICULTURAL ENGINEERING
EDMONTON, ALBERTA
SPRING, 1975

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "The Effects of Some Physical Factors on Dust Concentrations in a Pig Barn" submitted by Laurence Frank Honey in partial fulfilment of the requirements for the degree of Master of Science.

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ABSTRACT

Topics including particle properties, dust sampling methods, dust and hygiene, dust and odour and dust concentrations in animal environments were reviewed in the literature. Two levels of each of the variables relative humidity, air-flow rate, feeding method and pen volume were combined in a split-plot factorial design incorporating two Latin squares. This experimental design was imposed on four independent pens each containing ten pigs. Atmospheric dust concentrations were determined for six particle-size ranges using a cascade impactor and photomicrography particle-counting techniques. Settled dust concentrations were determined using open plates and gravimetric methods. Analyses of variance and covariance were performed on the data. The covariates were pen temperature during sampling and pig weight. Some of the more important conclusions were as follows. (i) The different size ranges of atmospheric dust were not similarly affected by the same treatments. (ii) Relative humidity of 90 percent resulted in a significantly greater amount of settled dust than did 65 percent relative humidity. (iii) Self-feeding was associated with a significantly greater amount of atmospheric dust than was floor-feeding, but the latter was associated with a highly significantly greater amount of settled dust than was self-feeding. (iv) Both atmospheric and settled dust were composed primarily of feed particles. (v) The more important factors associated with dust concentrations, in descending order, were considered to be; activity of the pigs, temperature, humidity with volume interactions, relative humidity, amount of feed fed, feeding method, pig weight, and air-flow rate.

ACKNOWLEDGMENT

The author acknowledges the financial support of the Canada Department of Agriculture.

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1. INTRODUCTION

Dust is and always has been important in the human environment. The importance of dust is not due to any beneficial qualities but rather to some undesirable characteristics of an aesthetic and hygienic nature. A dusty environment is considered dirty, unpleasant and not conducive to good health. Dust is a nuisance.

Industrial dust in its many aspects has been studied quite extensively and the results well documented. The reason for this is due primarily to the significance of dust in respiratory diseases of humans. However, dust in animal shelters apparently has not been studied to any appreciable extent. With the advent of large confinement livestock production units, dust in the environment has become increasingly suspect as a contributing factor in animal health and performance. As revealed in the literature, the detrimental effects of dust on animals have not been proved conclusively and many disease-producing microorganisms are only suspected associates of dust. Dust within the controlled environment of intensive livestock shelters also creates problems with the operation of mechanical equipment.

At present, the factors that determine the amount of dust in an animal shelter are not clearly identified. The scattered research, inconclusive results and unknown dust-agent relationships emphasize the need for more detailed studies concerning this aspect of environmental control in livestock housing. Accordingly, the objective of this project was to determine the effects, if any, of some physical variables including pen volume, air-flow rate, feeding system and relative humidity that might affect atmospheric dust concentrations in a pig barn.

2. A REVIEW OF THE LITERATURE

2.1 Dust Defined.

Dust may be defined empirically (13) as a powdered or finely divided form of homogeneous or heterogeneous solid substance, mixed with or without any regard to particle size difference, proportionality or condition amongst its parts. Other definitions of dust are available (85). The use of the term "dust" as a noun goes back to the German word "dunst" which expresses the primary notion of - that which rises or is blown in a cloud. Dust is earth or other solid matter so reduced to minute particles as to be easily raised and carried in a cloud by wind. Dust is any substance pulverized; that is, a powder. The word "dust" is often extended to include ashes and other similar materials from a house. Dust can be any small particle of dry matter. "Dust" is rarely used in the plural. As a verb, "dust" can mean: dusty; to reduce, or crumble, to dust; to sprinkle with dust or powder; to make dusty; to strew as dust; to free from dust, or to brush, shake or rub off as dust.

In this project, dust will be used as a noun denoting small particles - generally those particles within the environment of a research pig barn. The definition of dust as finely divided matter is accurate but inadequate, the reason being that the behaviour of any substance in the form of dust is so different from the normal behaviour of the substance when in a more massive form that a definition of dust as a particular and distinct state of matter is almost justified (44).

Dust particles may be liquid, as in mists and sprays, or solid, as in many fumes and smokes. When they are suspended in air or in any other gas, these particles if small enough will acquire, in response to a ceaseless bombardment by the molecules of the surrounding gas, a mobility (Brownian motion) that resembles the vigorous motion of the molecules themselves (22,44). Thus, the dispersed liquid or solid may be said to be masquerading as a gas and also to appear to possess a greatly diminished density since it floats in air. After being dispersed in a gas, particles occupy a very much greater volume. The dispersed dust particles possess increased physical and chemical activity and can exert a pressure on the walls of a container. However, the low transparency of dispersed particles to heat and light conceals the true solid or liquid character of the particles.

Dust particles range in size from the fine sand or grit (0.1 mm in diameter) that is blown about on a windy day to the minute particles (0.00001 mm in diameter) that make up cigar smoke (44). The rate at which a particle settles in still air is directly proportional to the density of the particle and its radius squared (44). Small particles such as smoke particles do not settle at all but are driven about randomly by the enveloping gas molecules, with a very much greater velocity than that due to gravity. Owing to this low gravitational settling velocity, fine particles remain in suspension a sufficient length of time to form a comparatively stable system. Familiar natural examples are fogs, mists, smokes and clouds.

Any two or more phase system in which a finely divided solid or liquid is dispersed in a gas is called an aerosol. When the amount of the gas phase is relatively small, the system is called an aerogel. Generally, an aerosol may be regarded as dust in suspension and an aerogel as dust in a heap (44).

The heterogeneity of dust is accounted for because all materials to a greater of lesser degree are liable to form dust (13). The process of disintegration or degradation of materials to form dust particles is continuous. Dust is the end product of most substances. In a sense, and a very real sense, the earth is one large dust heap.

2.2 The Staubosphere.

Coexistent and probably coextensive with the earth's atmosphere is an immense continuously-existing solid particle system. This sytem, of the same order of importance as the atmosphere in its interaction with life on earth, merits according to Blacktin (13) the definite individual title of "staubosphere". "Staub" is derived from the present German word for dust while "sphere" indicates the natural all-encompassing domain of that dust. The coexistence of the staubosphere and the earth's atmosphere is one of extension in time and space rather than variation of quality or quantity.

2.3 The Formation of Dust.

Dust may be formed by the condensation of a vapour or by the disintegration of a liquid or solid (44). In most cases in industry and agriculture, dust is produced by a disintegration process.

The degree of fineness that can be obtained by disintegration processes is limited and is much less than that which can be obtained by the condensation of a vapour. A solid substance may be disintegrated by the application of shearing forces, tensile stresses, crushing pressure or sudden blows. A liquid is relatively easy to disintegrate owing to its relatively low viscosity.

2.4 Dust Classifications.

Most dust classification systems are based on either the parent material, shape, size or method of formation of the particles.

The difficulty of classifying dust can arise from the ambiguity between aggregates and the ultimate particles constituting those aggregates.

Blacktin (13) categorized dust as earth-formed and cosmic; each either dispersed as an aerosol or settled as an aerogel. Mason, as cited by Blacktin (13), classified the mechanization of aerosol formation into the following groups; condensation and sublimation, chemical reaction, mechanical disruption and dispersal, coagulation, and the influx of intraterrestial particles.

The characteristics of particles at different locations in the staubosphere are affected by such things as the proximity of land masses and bodies of water, weather patterns, centres of civilization, the state of industrialization of these centres and the geography of the near land masses (13). Particle counts in the staubosphere also vary dramatically with different localities and conditions. Blacktin (13) cites the records of various workers to give some idea of the variation in particle number with height above ground and locality. Less than one-hundred particles per cubic centimeter were rarely found. Particle counts generally increased with increasing human activity.

Particle-size may be regarded as the criterion for zoning the staubosphere (13). However, by applying the law of gravity, Stoke's Law (22,40) and Cunningham's Law (13,22) to particle-size, the staubosphere can be zoned according to the chief respective characteristics of settlement. Thus, the three zones of the staubosphere would be; (i) those particles of radius greater than 0.01 centimeters (cm) settling with rapidly accelerating velocity due to gravity, (ii) those particles less than 0.01 cm radius and greater than 0.00001 cm radius settling with slower decelerating velocity in accordance with Cunningham's Law.

Gibbs' (44) three kinds of aerosol distinguished according to the size of particle and degree of dispersion are dust, clouds and smokes. These correspond respectively to Blacktin's (13) three dust zones; gravitational, Stoke's, and Cunningham's. Dust is formed of those particles which are larger than 0.001 cm in diameter. Such particles settle in still air with increasing velocity and do not diffuse. Clouds are formed of particles ranging in size from 0.001 cm to 0.00001 cm in diameter. Such particles settle in still air at a constant velocity and do not diffuse. Smoke is composed of particles less than 0.00001 cm in diameter. Such particles are in active Brownian motion, diffuse fairly rapidly and do not settle at all in still air. The primary differentiation between each of these classes is really based on particle settling velocity rather than on particle-size.

According to Dorman (36) and Drinker and Hatch (37), particulate matter may be classified in the generalized categories of dust, fumes, smoke and mist. The separations between these classes are based on the respective formation processes: mechanical disintegration of solids; condensation, sublimation, and chemical combustion; organic combustion; and condensation of vapours or atomization of liquids. These categories do not include individual particle-size separation ranges.

The system discussed by Cadle (23) for particles suspended in the atmosphere defines three size ranges; (i) "Aitken particles" are those with radii less than 0.1 micron*, (ii) "large particles" are those having radii in the range 0.1 to 1.0 micron, and (iii) "giant particles" are those having radii greater than 1.0 micron. The term "Aitken particles" has resulted from the development and use of the Aitken nuclei counter.

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* 1.0 micron (micrometer, μ) $=10^{-6}$ meter = 0.0001 cm.

This device is essentially an expansion-type cloud chamber in which water condenses on the particles contained in a sample of air.

There is no standard dust classification system. Each researcher has usually developed a system which suits, or is inherent to, the particular aspects of any singular study of dust.

2.5 Particle Properties.

Properties which control the physical and chemical behaviour of the individual particles in an aerosol include size, size distribution, shape, specific gravity and surface characteristics (103). Many of the physical and chemical properties of finely-divided solid and liquid substances are independent of particle-size, whereas others vary to some degree as a function of size. These variations may be used as an index of size for specific materials.

Properties relating to the surface characteristics of small particles include specific area, rate of evaporation and condensation, electrostatic charge, adsorption, adhesion and light scattering (103). Particles in aerosols are sufficiently small to exhibit some collodial properties and to possess properties different from those of the parent materials. Changes in the environment of a particle during sampling and size analysis may change some of the properties of the particle. These changes must be considered in the selection of both a suitable sampling device and the method to be employed for particle-size analysis.

2.5.1 Size.

The term "particle-size" as so often used is very indefinite and even when applied to spheres can mean either radius or diameter. Numerous definitions of particle-size have been developed to avoid such ambiguity. The size can be defined as either a statistical property based on the measurement of each of a large number of particles or in terms of some property of the particles, either individually or collectively, which is related to particle-size (22,23).

There is no standard method of measuring particle-size. However, Silverman et al (103) have presented the most common definitions of size as follows.

(i) "Aerodynamic diameter" or "kinetic diameter" is the diameter of a hypothetical sphere of unit density having the same terminal settling velocity as the particle in question, regardless of its geometric size, shape and actual density.

(ii) "Count median size" is a measurement of particle-size for samples of particulate matter, consisting of that diameter of particle such that one-half of the number of particles is larger and the other half is smaller.

(iii) "Feret's diameter" is the normal distance between two parallel tangents to the extreme points on the particle measured in a consistent manner.

(iv) "Green's diameter" is the average diameter of a hypothetical particle that is in some way representative of the particles in the sample.

(v) "Martin's diameter" is the distance between opposite sides of the particle, measured in a consistent direction, such that the diameter bisects the projected area.

(vi) "Mass median size" is a measurement of particle-size for samples of particulate matter, consisting of that diameter such that the mass of all larger particles is equal to the mass of all smaller particles.

(vii) "Projected diameter" is the diameter of a circle of area equal to that of the projected area of the particle.

(viii) "Stoke's equivalent diameter" is the diameter of a hypothetical sphere having the same terminal settling velocity as the particle in question and having the same density as the particle material.

When irregular particle shapes are characterized by a single dimension that is measured in a consistent way, particle surface area and volume may be assumed to be functions of the same linear dimension, and area and volume can be estimated by applying appropriate shape factors. Typical values of shape factors as determined by various workers have been compiled (37,103). The preferential orientation of suspended and deposited dust particles may produce changes in their measurement as large as fifty percent (103).

Silverman et al (103) found that the total surface area of a collection of particles was approximately equal to a constant multiplied by the square of some average diameter of the collection of particles, over a reasonable range of sizes. A similar empirical relationship was found to exist between the total volume of a collection of particles and their average diameter.

According to Drinker and Hatch (37), the size variation in a series of particle measurements in a sample of non-uniform dust was best shown by a size-frequency curve. This curve could then be converted into a logarithm-probability curve that has considerable practical value as a mathematical means for describing particle-size distribution.

2.5.2 Shape.

Particle shape is influenced by the method of formation (103).

If formed by disintegration or attrition processes, then the particles thus formed will resemble the parent material. If formed by condensation of a vapour, the smallest unitary particle could be spherical or cubical. Changes in particle shape can result from crystallization, solidification, hydration, agglomeration or some other such processes.

The problem of quantitatively defining the shapes of dust particles has been studied by various workers as reported by the Engineering Equipment Users Association (40). Drinker and Hatch (37) proposed the use of shape factors to indicate the effect of shape upon the size of irregular particles. Irregular particles also can be assigned an arbitrary linear dimension in accordance with a definition of size (as discussed in Section 2.5.1). The frequent assumption that dust particles are spherical often purposely neglects the known irregular shape of the particles. The assumption can be tested by comparing actual shape factors to the assumed spherical (or other) shape factor.

Most dust particles are shaped irregularly. Silverman et al (103) considered the more important shape of dust particles to be the sphere, the rod, the fiber, the cube, the flake, the floc and the aggregrate. Other common shapes include splinters, platelets, rectangles and acicular forms (40).

2.5.3 Surface Area.

One of the important characteristics of small particles is the rapid increase in surface area per unit mass as size decreases (103). The greatly increased exposed-surface area associated with fine particle suspensions leads to increased chemical reaction rates and increased electrical capacity. The relationship of surface area to particle-size was discussed previously (Section 2.5.1).

2.5.4 Evaporation and Condensation.

Evaporation and condensation is a diffusional mass transfer process that proceeds in proportion to the surface area exposed (103). Small particles can act as centres for condensation of moisture, leading to an increase in their size. This phenomenon has some bearing on the growth and deposition of fine particles in warm humid air such as during inhalation (37) and in so-called "sweat-box piggeries" (47,48).

2.5.5 Electrostatic Charge.

Electrostatic charge represents an excess (-) or deficiency (+) of electrons on the particle. Most small particles have naturally acquired charges by electron transfer during contact or separation or because of free ion diffusion (103). Grudge, as cited by Gibbs (44), suggests that in most cases dust particles become charged by contact with one another, with the sign of the charge acquired by the large particles being opposite to the sign of the charge acquired by the small ones. Dust can also become charged as a result of friction against a solid surface (44). If the solid surfaces (for example; ventilation ducts and feed mills) are not grounded and favourable conditions are present, particularly a dry atmosphere, an electrical discharge of explosive force can occur between the charged dust particles and the solid object (82).

Collision and agglomeration of oppositely-charged particles affects sedimentation rates of dust and may lead to false size data (103). Bundy et al (17) studied the effects of the ionization of dust particles and subsequent agglomeration as a technique for removing dust from a pig barn.

2.5.6 Light Scatter.

Scattering of a light-beam arises from heterogeneities such as dust in the fluid medium through which the light-beam is passing. Scattering is often accompanied by absorption, and both scattering and absorption remove energy from the beam of light. The quantitative response of an attenuated light-beam can serve to characterize the size of the particles causing the attenuation (103).

2.5.7 Adsorption.

Small solid and liquid particles are surrounded by a surface film of gas held by unbalanced electrical or chemical valence forces originating in the surface molecules (103). Gradually and to a limited extent, the adsorbed gases will diffuse to the interior of the solid. Thus, dust particles absorb some of the adsorbed gases. Many substances when reduced to fine powders will flow like a liquid, the particles being cushioned by adsorbed gases and, therefore, able to move freely over one another. Many surface characteristics of small particles, including electrical charge, adhesion, and evaporation, are modified by the presence of adsorbed gases (103).

2.5.8 Adhesion.

When a layer of liquid is spread between surfaces in contact, adhesive forces are produced in proportion to the surface tension of the liquid and the radius of curvature of the liquid pool. Water vapour is adsorbed on many surfaces exposed to ambient atmospheres so that the force of adhesion can be related directly to the humidity of the air. Silverman et al (103) cite the work of Corn and Zimon as references for more detailed discussions on some of the practical aspects of other factors concerning the phenomenon of particle adhesion.

2.5.9 Chemical Activity.

The rate at which two given substances react chemically depends upon the facility with which they can be brought into contact with one another (22). At any particular moment, chemical reaction is necessarily restricted to those molecules that are actually situated at the surface of contact; consequently, the reactivity of any substance is a function of its specific surface. The chemical reactivity of any substance, therefore, is increased by disintegration in the following two ways; (i) owing to the greater specific surface, a given reaction can occur more readily and more rapidly, and (ii) owing to the resulting greater surface energy of the individual particles, each particle can react more readily. So great is this effect that many substances which in a comparatively massive condition burn in the air with difficulty can burn, when dispersed in the air as dust, with explosive violence (44).

2.5.10 Stability of Aerosols.

When dust particles are suspended in a gas to form an aerosol, they are in a condition of unstable equilibrium. They will be removed gradually from the gas by settling, deposition or diffusion (44). The molecular bombardment of particles less than 0.1 micron in diameter will effectively prevent them from settling at ordinary temperatures and pressures.

The removal of particles by deposition can be accelerated by stirring, whereby the increased collision frequency between particles leads to the formation of relatively coarse aggregates or flocs which settle rapidly (44). The introduction of solid surfaces into a dust-laden atmosphere reduces the travelling distances and increases the chances for particles to contact deposition sites, thus hastening the settling of dust. This is the principle underlying the process of aerosol filtration (44).

The natural tendency of an aerosol to form flocs is frequently inhibited by the presence on the particles of adsorbed gas or of electrical charges of like sign. The adsorbed gas can sometimes be displaced by introducing a more readily adsorbed vapour into the aerosol or by dislodging the adsorbed gas by some violent mechanical disruption (44). The increased stability that is due to the particles carrying electrical charges of the same sign can be overcome by introducing particles that are charged oppositely so that attraction and aggregation are induced. The aerosol can also be subjected to a suitable potential gradient so that the charged particles travel in the same direction and are ultimately deposited on an electrode (12,44).

2.5.11 Solids - Loading.

Solids-loading is a measure of particulate concentration in a gas. Although not strictly a particle property, it can be considered a property of the staubosphere. Solids-loading can be expressed in terms of weight per unit volume of gas or in terms of the number of particles per unit volume of gas. Generally, a high concentration of particulate matter is expressed in units of grams per cubic meter, a moderate concentration in units of milligrams per cubic meter, and a light dust concentration in units of micrograms per cubic meter or the number of particles per unit volume (103). Exact conversion of dust concentration values from weight to count or from count to weight is impossible unless the size and density of the dust particles are known, the collecting efficiency of the sampling instrument in relation to particle-size is established and the size limits are known (37,58,103).

2.6 Sampling Methods.

This section surveys some of the various techniques of particle-size analysis and particle-size distribution analysis.

Drinker and Hatch (37) consider only two types of dust surveys; hygienic surveys made to study the relationship between dust and ill-health, and engineering surveys made to determine sources of dust or to check the effectiveness of dust-removal equipment. This project is an engineering survey that is primarily concerned with the hygienic size-range of dust particles.

Sampling instruments for particle sizing may be divided into two functional groups; (i) those that capture a bulk sample of particles in a convenient form for transportation to an analytical laboratory, and (ii) instruments that while collecting a sample, affect in some fashion a size separation or classification of particles that becomes an integral part of the subsequent analytical procedure (103). Not only must a collection method give a representative sample of the material, but it must not alter the basic ambient particle-sizes of the collected dust.

Sampling times for determining dust concentrations may be a few seconds, several minutes or many hours. In the case of active dust-producing processes, dust concentrations are subject to rapid fluctuation. Sometimes a single dust reading has a fifty percent chance of falling outside as well as inside the limits of the error of the mean for a sample of dust. These fluctuations are likely to be normal and not exceptional events (37).

Particle concentration and the time available for sampling exert an important influence on the choice of sampling instrument. A number of instruments are suitable for obtaining instantaneous samples of an aerosol containing light dust loadings whereas others can be used to collect large amounts of dust over either very short or very long periods (37). Instantaneous sampling instruments provide an excellent means for following the variations that occur during a cyclic or irregular process, as well as for capturing a dust sample from an operation of very brief duration. Long-term samplers provide information on average conditions over some appreciable time interval.

No definite rules have been established for the location of the sampling point, the volume of sample to be collected, and the frequency of sampling since conditions and practical limitations vary from problem to problem. An investigator must rely on common sense and experience in determining these criteria (37).

2.6.1 Sieves.

Sieves are used for sizing relatively coarse particles, generally larger than forty-four microns (58). Sieving procedures have been standardized (51). Fine screens with apertures as small as 18 microns require specialized equipment and cumbersome analysis techniques.

2.6.2 Sedimentation.

Sedimentation methods for sampling and sizing dust particles are based on the measurement of the settling rate of particles in fluids (58). Settling velocities are obtained directly and equivalent diameters indirectly, based on known or assumed laws about the flow resistance of the particle as discussed in Section 2.4.

The simplest method of sampling a dusty atmosphere, by exposing a plate in the open, provides a biased sample. The greater terminal velocity of the large particles ensures that the sample contains a much higher percentage of these particles than does the staubosphere being sampled. In order to obtain a representative sample, various types of sedimentation cells have been developed (36).

As well as being used to obtain samples of particles, sedimentation may be used for size analysis (103). One technique allows a sample to settle in a stationary column of special dispersant fluid. Density measurements at known intervals and at certain levels provide data for the calculation of the particle-size distribution. Another method used the decrease in light obscuration of a small beam of light with time after the start of sedimentation to obtain indirectly the particle-size distribution of a dust sample. One additional method requires the use of photographic plates to record the track of individual particles while settling. The size of each particle is estimated from the length of its track, since sedimentation rate depends upon size.

2.6.3 Centrifugal Force.

This method is similar to that of sedimentation analysis but uses centrifugal force rather than the force of gravity. The force in some ultracentrifuges may be as high as one-million times that of gravity. This extends the lower particle-size limit that can be determined to about 0.01 microns (58).

2.6.4 Elutriation.

This method separates particles in a vertically rising fluid (58). Fine particles larger than a certain cutoff size are carried upward with the rising fluid, particles smaller than the cutoff size fall to the bottom of the elutriation chamber. A series of graded elutriation chambers may be used to separate particles into size classes.

2.6.5 Filtration.

Filters can be used to collect large samples of airborne dust and other particles for later size analysis. In all cases, sufficient dust must be accumulated on the surface of these filters so that the portion used for sizing contains the correct distribution of sizes. Particle-size reduction due to shattering is an inherent problem with the use of filters (103).

2.6.5.1 Soluble Filters.

After sampling, the porous bed of soluble or volatile material is dissolved or volatilized leaving the dust behind. Soluble filters have little value for particle-size analysis since the dissolution of the filter and the concentration and recovery of the collected dust may drastically change the size and state of the original particles (103).

2.6.5.2 Membrane Filters.

Membrane filters are manufactured from cellulose-esther gels that are dried in the form of thin (1.50 microns) porous films of controlled pore size (103). They retain airborne dust as small as 0.001 microns. With careful collection, dust will be deposited on the filter in the state in which it existed in the sampled air. The collected dust can then be examined microscopically "in situ". Membrane filters have been widely used in livestock-dust studies (1,10,24,34,35,72,74,75).

2.6.5.3 Fibrous Filters.

Deep beds of filters composed of natural, synthetic or mineral fibers of small diameter make excellent low resistance, high-efficiency dust filters. However, they are of little value for dust sampling, particularly particle-size analysis (103). Fibrous filters have been used by agricultural researchers studying the hygienic significance of dust in animal buildings (38,80).

2.6.6 Impaction.

Particles in this sampling method are impacted on a plate by a jet of air (3,103). A series of graded impactors, the so-called cascade impactors, may be used to separate particles into size classes. The particulate cloud to be sampled is drawn through the first set of equal orifices at a fixed flow rate, onto a glass slide mounted normal to the flow of the air-jets. Particles with sufficient inertia strike the plate and generally adhere. The air, which contains the remainder of the particles, is subjected to a ninety-degree change in direction and passes through another set of equal orifices of smaller size. The resulting higher velocity through these smaller orifices causes impaction of particles smaller than those that adhered to the first plate. This process can be repeated and staged such that size classes of particles are obtained. The plates may be coated with adhesive in order to reduce the breakup of aggregates. However, the coating may interfere with microscopic sizing (37).

The cascade impactor is used mostly for sampling particles in the one to twenty micron size range. Drinker and Hatch (37) report that the collection efficiency of standard impactors varies directly with sampling rate and inversely with the particle-sizes of the collected dust.

According to Wells, as cited by Andersen (3), the aerodynamic dimension of a particle rather than its actual size is of more concern, especially in respiratory penetration studies. Thus, a cascade impactor should be calibrated in terms of smooth, spherical particles of unit density so that any and all particles collected in the sampler, regardless of their physical characteristics, could be assigned an effective size, or aerodynamic dimension, according to the stage on which they were collected. The assigned value would be equal to that of the spherical particles collected on the same stage. The calibration method discussed by Drinker and Hatch (37) was essentially the same.

Andersen (3) found that aerosols of Carnauba wax and Krylon were satisfactory for the calibration of the sampler. He also stated that the Andersen Air Sampler, a cascade impactor, efficiently collected and separated into six size ranges particulate airborne matter larger than one micron. This matter included microbial particles such as bacteria, yeasts and moulds, as well as non-viable particles such as dust, smoke, and pollen. Agar medium was found to be an excellent collecting surface for some of these particles (3). Microscopic examination of collected material can be made directly on the collection plates.

2.6.7 Photometry.

The use of photometry, or the measurement of light intensity, is based on the scattering or absorption of light, as discussed in Section 2.5.6, both of which depend on particle-size (58). This method is most useful for determining solids-loading of fine particles smaller than a few microns in size. The lower size limit is 0.03 microns for a uniform particle-size dispersion.

2.6.8 Microscopy.

The maximum resolving power of optical microscopes permits determination and identification of particles as small as 0.5 microns in diameter (58). Difficulty and error may arise from the inherently small quantity of material analysed, the consequent problems of obtaining representative samples in a satisfactory state of disperison, the tedious nature of the determination and/or the liability to err both systematically and subjectively due to the process of visual size classification and counting.

The use of optical microscopes allows the identification of dust by such characteristics as particle shape and colour. The microscopic examination of coarse material, larger than five microns, with low magnification is a relatively simple matter requiring no great care in the choice and manipulation of the optical system (37). The linear measurement of objects under a microscope may be accomplished in three ways; (i) by comparison with a scale incorporated in the ocular of the microscope, (ii) by projection of the microscopic field upon a screen where the enlarged images could be compared to a suitable scale, and (iii) by the use of a vernier scale on a moving mechanical stage. The first method is the most accurate because it is the most direct (37).

2.6.9 Precipitation.

The precipitation of atmospheric dust particles is due to either a thermal or electrical gradient across a narrow duct through which a sample of air passes (37,103). Limitations of precipitation methods include low flow rates, the unknown effects of heat or ionization on the collected particles and size gradations in the dust deposit. The most valuable features of the use of precipitators are their ability to collect particles as small as 0.1 micron and smaller at close to one-hundred percent efficiency, the fact that collection efficiency is unaffected by either high or low dust concentrations and their ability to collect dust particles in the same form as they existed in the air. Use of the electrostatic collection of particles is limited to nonexplosive atmospheres.

2.6.10 Automatic Methods.

There are very great and obvious advantages in making microscopic size analysis fully automatic by incorporating mechanical scanning together with some form of photoelectric detection and high speed pulse counting (103). A number of automatic particle counters and sizers are available commercially. These are costly. Phenomena that have been used in these systems include detection of light scattered from individual particles passing through a light-beam, measurement of electrical properties or the motion of charged particles, acoustics, momentum and heat transfer.

2.6.11 Isokinetic Sampling.

Representative samples of particulate materials greater than a few microns in diameter may be obtained from rapidly moving gas streams only when sampling is conducted so that the flow rate at the entry to the sampling probe is at the same velocity as the main gas stream (103); that is, the velocities must be isokinetic. When the velocity into the sampling probe is different from that of the main stream, that is, anisokinetic, the size distribution and the solids-loading of the particulate matter collected will be different from that of the main stream. The explanation lies in the behaviour of particles having sufficient mass and/or velocity to possess appreciable momentum and thus bypass the stream-flow lines around the sampler probe.

2.6.12 Photography.

According to Drinker (37), photography should not be used as a substitute for dust measurements. However, photographs may show something which dust samples do not show. The determination of changes in dust concentrations resulting from changes in procedure and the location of different sources of dust could be a valuable use of photography.

2.7 Comparison of Sampling Instruments.

Unsuccessful attempts have been made to determine relationships between dust concentration measurements obtained by the several dust sampling instruments and counting techniques to provide a basis for comparison of results for conversion of concentration measurements by one instrument to equivalent values for another instrument. Drinker and Hatch (37) report that there is not even an approximate conversion factor that can be used for comparing dust concentrations determined by two different instruments. There are two main reasons why no conversion factor can be obtained; (i) the collection efficiency in relation to particle-size differs significantly among the various instruments, and (ii) a varying degree of disaggregation occurs in the course of collecting dust using different samplers.

The electrostatic and thermal precipitators and various filters are superior to the impaction-type instruments with respect to collection efficiency in relation to particle-size (37). Membrane filters, thermal precipitators and impactors have the advantage of depositing the dust from the air in such a way that permits direct microscopic examination.

Drinker and Hatch (37) suggest that a dust sampling instrument is needed which, in the course of operation, will separate the dust into several size fractions of hygienic interest without altering the particle characteristics and will deposit the particles in such a way as to permit all necessary physical and chemical analyses. The number and size of particles, the surface areas, weights and significant chemical and mineralogical characteristics should be reported for each size fraction of a dust sample. The collection and enumeration of particles smaller than one micron should not be included in the dust count which represents a specific treatment exposure since such fine particles are commonly present in large numbers in polluted air and may be extraneous to the specific treatment. The cascade impactor attempts to meet these requirements (3,37). However, important limitations include; (i) the amount of the collected sample is limited and lends itself only to micro-analytical methods, and (ii) the measure of the amount of small particles in the sample may be distorted because of disaggregation by impaction.

2.8 The Hygienic Significance of Dust.

Exposure to dust can produce several distinct types of disability in mammals (37): (i) pneumoconioses, which includes all pulmonary manifestations of dust inhalation whether the dust is injurious or harmless; (ii) toxic effects produced as the result of either breathing or ingesting certain dust such as lead; (iii) metal-fume fever caused by the inhalation of certain metallic-oxide fumes; and (iv) an allergic reaction. Dust inhalation is the usual cause of disability; only in the cases of a few types of dust are there other modes of particles entering a living body. An accepted rule in hygienic surveys is that the finer the size of the particle and the greater the dispersion then the greater is the health hazard (37).

2.8.1 Respiration and Dust Inhalation.

Mammalian lungs (34,37,74) are non-symmetrical bilateral structures encased in a somewhat elastic cavity, the chest. They communicate with the nose and mouth through the trachea, or windpipe. The trachea branches into the bronchi, and these in turn subdivide into bronchioles which lead to the terminal air sacs, or alveoli. Gas exchange, the whole purpose of respiration, takes place in the alveoli between the blood and the inhaled air. Oxygen is taken up by the red blood cells and carbon dioxide is given off. High air velocities occur momentarily in the trachea. The velocity in the alveoli is practically zero at all times since each alveolus is the end of the air-flow path. Thus, there can be no high-speed impaction of dust particles into the lung tissue.

Dust particles larger than fifteen microns are likely to be caught in the nasal passages or at the back of the throat (37). If such a particle should be transported along the centreline of the trachea, there is no reason why the particle should not pass on to the bronchi, but it is not likely to reach the alveoli. The collection of such particles is solely the result of chance impact against the moist walls of the respiratory tubes. Such impact takes place most effectively with particles having appreciable momentum due to their large size and rapidly ceases to be effective as the particles approach sizes at which they move as an integral part of the transporting gas.

Lining the trachea and extending to the lower ends of the bronchioles are thousands of cells with whip-like appendages, cilia, which carry upward any foreign particles that chance to touch the wet mucous-lined respiratory passages (37). The nasal passages are also bathed in mucous and lined with cilia. The mucous constantly moves toward the exits of the nose and mouth where it is expelled from the body. Within the alveoli, there are no cilia and there is no mucous. However, within the alveoli are other cells, phagocytes, which are produced in vast hordes by the stimulus of foreign bodies that are then engulfed by the phagocytes.

The dust-laden phagocyte cells, having the power of independent motion, may pass through the walls of the lung tissue into the lymph fluid and thence into the capillaries surrounding the lungs, or they may pass through the finer bronchioles through which they are removed by ciliary action. Most of the dust-laden cells migrate into the lymphatic system, which starts as a meshwork of fine vessels that drain the tissue spaces. These fine vessels come together forming larger and larger vessels that finally discharge the lymph fluid into the blood stream (37). The blood stream is then cleansed by the action of the liver and kidneys.

A great deal of dust is deposited by the phagocytic cells at the tracheal-bronchial lymph nodes, one function of which is the filtration of foreign bodies. The disability of healthy lung tissue most often starts at this location. Dust particles can be phagocytosed at any point in the lymph system. All dust particles are not phagocytosed with the same readiness and the rapidity of migration of cells differs with different dust.

Andersen (3) considered those particles less than 5.2 microns in diameter as hazardous since these are the particles which can penetrate the lung. Particles greater than 5.2 microns were considered non-hazardous.

Some of the effects of dust on the respiratory system have been summarized by Martin (74). Particulate-size influences only the site of deposition and does not directly influence the respiratory clearance rate. Particles greater than five microns in size generally are removed at various sites in the larger air passages. Particulates of approximately one micron in size are capable of penetrating the alveoli. An important property of dust that affects its size range is the extent to which a given particle acquires moisture and thereby enlarges as it passes through the moist respiratory tract. Organic particles, which are usually quite hygroscopic, may increase substantially in size by this process. Soluble and insoluble dust particles are considered together in matters concerning particle deposition, the only difference being the growth in size of the more easily wetted particles. Most highly soluble deposited material passes into the gastrointestinal tract.

The effect of dust on the respiratory tract is primarily influenced by the amount and size ranges of dust particles (74). However, other physical, chemical and aerodynamic properties of the dust must be considered. The amount of dust to which an animal is exposed may influence the degree of damage caused to the alveolar area. However, the amount of dust does not appear to have any effect on the foreign particle removal mechanism of the tracheal-bronchiol system. These observations by Martin (74) must be tempered by an appreciation of the fact that the deposition and clearance of dust is not usually a uniform process throughout the respiratory system. The pulmonary response may be influenced by temperature and relative humidity. Generally, ciliary movements respond directly to temperature changes. Low relative humidity of respired air will dry the mucous system and prevent normal movement of the particle-laden mucous blanket. Equally important as the ambient temperature and relative humidity in influencing the pulmonary response is the rapidity of the changes in these parameters (74). Ciliary movement can be impaired by the action of toxic gases and microbial agents.

2.8.2 Livestock Pulmonary Problems Associated with Dust.

The assessment of pulmonary air pollution effects requires the calculation of dosage as well as dust concentration. Weber (113) differentiates between these effects, one as a function of concentration, and the other as a function of concentration multiplied by time which is defined as dosage. The time is the period that the particle remains in the body. A threshold value or limit concentration would enter into the calculation of time. Possible recuperation intervals also must be considered.

In order to establish respiratory disease, a virulent organism must be deposited in a critical location appropriate to the disease (37). Dust particles are suspected carriers of virusses and bacteria (38,52,89,93,94,95,96). The size of the transporting dust particle plays an important role in carrying a micro-organism to a suitable location for either survival resulting in the hibernation of the disease to reappear later, or growth and reproduction resulting in the ravages of disease.

Rest (93) commented on the bio-engineering aspects of livestock environment contamination. The discussion centred around micro-organisms on the farm, the engineering aspects and the systems approach. He concluded that livestock environments can contain important numbers of micro-organisms. Circumstantial evidence suggests that these micro-organisms are directly hazardous to the health of animals and indirectly hazardous to the health of consumers of livestock products. Not all organisms can affect all animal species. However, many classified diseases affect both man and lower vertebrates. The number of shared micro-organisms causing or aiding minor ailments cannot be assessed. Contamination sensitivity information and disease transmission-route control criteria have not been fully developed. As a result, disease control can receive only limited consideration in livestock-facility design.

The literature reviewed in this section and the following sub-sections indicates that dust is of substantial importance with regard to livestock respiratory diseases. While evidence of direct adverse effects of dust on pulmonary disease is lacking, the association of dust with airborne infections suggests that more attention should be accorded to dust in environmental control, especially within confinement housing.

2.8.2.1 Poultry.

Harry (52) concluded in a study of coliforms found on samples of dust from poultry houses that *Escherichia coli* was the predominant coliform. This strain belongs to the same group as those responsible for coli-septicaemia outbreaks in intensively housed poultry. Roller (96) found a direct relationship existing between the numbers of *Escherichia Coli* and relative humidity for both dry litter and dust. He noted that a demand existed for more knowledge of the airborne environment, including gases, dust, odours, heat, and its effect upon animals and equipment.

Drury (38) reported that a filtered-air-positive-pressure ventilation system showed some promise in controlling the highly contagious viral diseases, Marek's disease and infectious bronchitis. The method involved the high-efficiency filtration of the incoming air and the maintenance of a positive air-pressure inside the poultry house. The fundamental premise was that the filters removed airborne particles and insects which could carry pathogenic organisms, while the pressure differential caused the air to move outward rather than inward when doors were opened or when leaks occurred.

Broiler performance (101) was shown to be much superior in dust-free pens than in field conditions,probably because of the presence of airborne diseases affecting the respiratory tracts of the birds in the field. The presence of airborne diseases was observed (30) in emptied, cleaned and disinfected poultry houses but in lesser quantities than in occupied houses. This observation suggested that permanent broiler production would increase the danger of infections of airborne diseases.

Data obtained from four hatcheries (43) indicated a positive correlation between general hatchery sanitation and livability of chicks up to two weeks of age.

Poultry house dust was found by Beasly, as cited by Lillie (70) to be a major vehicle for the transmission of Marek's disease. Jurajda and Klimes (60) reported that dust collected from infected poultry houses retained its Marek's disease infectiousness for a period as long as forty-four days. Prince et al (89) observed fewer cases of Marek's disease with increasing removal of airborne particles by filtration. Their results (89) showed that the length of time of exposure to infectious dust-laden air was directly related to both the number of cases and the severity of cases of Marek's disease.

Mitchell et al (80) discussed the design of a controlled-environment cabinet for poultry disease-transmission research. Particles as small as from one to five microns were removed by passing the exhaust air through a medium-efficiency filter and two high-efficiency filters.

2.8.2.2 Cattle.

A fog-fever syndrome (73) occurs in Great Britain among cattle being kept in total confinement where they are exposed to atmospheric dust and mould. The symptoms of fog-fever in Britain are very similar to those of emphysema in the United States. Death from fog-fever is not common.

The exposure of forage crops to cement dust in the vicinity of cement works has affected the health of cattle and the amount and quality of milk produced (91). Raymond and Nussbaum (91) found no evidence of respiratory diseases among humans, animals or plants living in the neighbourhood of cement works, although respiratory diseases were noted among cement workers. Fly-ash dust was found to have a detrimental effect on cattle (76).

2.8.2.3 Pigs.

In a study of piggeries, Hoffman and Richter (56) found that a high number of germs in the air had a bad influence on the health and production of feeder pigs. A micro-organism concentration of 250 germs per liter of air was the recommended maximum standard for piggeries. Another recommendation was that dry feed should be pelleted rather than ground to reduce both dust and micro-organism concentrations in the atmosphere.

Kovacs et al (62) reported on the effects of some environmental factors on the health and production of pigs. Post-mortem examinations were performed on the lungs of animals taken from four enclosed finishing barns and two farrowing houses. Eighty-seven percent of the pneumonia cases were in pigs from the finishing pen with the highest dust concentration. However, the most severe pneumonia cases were found in the less dusty but heated pen with a high ammonia level. Kovacs et al (62) were of the opinion that the ammonia and the micro-dust equally irritate the deepest part (alveoli) of the respiratory tract.

Martin (74) and Martin and Willoughby (75) studied the relationships between organic dust, sulphur dioxide and the respiratory tract of pigs. The exposure of piglets to corn dust alone caused no clinical or pathological changes. However, when combined with sulphur dioxide both corn dust and corn starch produced lesions in piglets' respiratory systems. Clinical changes included occular and nasal irritation with increased salivation and central nervous-system depression. Cilia were lost from the epithelium of the larger bronchi following exposure to corn starch and sulphur dioxide. No changes in the respiratory area of the lungs were attributed to exposure to either dust or sulphur dioxide.

The effects of ammonia and organic dust were studied by Doig (34) and Doig and Willoughby (35). Eye irritation was observed in piglets exposed to ammonia, and ammonia combined with corn starch dust. No irritation was observed in the group of piglets exposed to corn starch dust only. Histopathological changes, primarily swelling of the linings, were limited to the nasal and tracheal epithelium. There was no evidence of structural damage to the bronchial epithelium or to the alveoli of the exposed piglets. No changes were observed in the appetites, average daily gain, frequency of coughing, hemograms, or total lactic dehydrogenase activity, that could be attributed to the dust and ammonia exposures.

Anderson (6) revealed an interesting case of methemoglobinemia poisoning in pigs arising from the presence of thick layers of dust in a ventilating shaft. The dust contained a small percentage of nitrite which, when in contact with water, became a toxic solution. The solution dripped to the floor where it was consumed by the pigs. The smaller the particle-size and the greater the particle density, solubility, relative humidity, activity of animals and concentration of pathogenic airborne bacteria, the greater was the degree of toxicity.

2.9 Dust Explosions.

Nawrocki (82) discussed the fire hazard associated with grain dust around farm machinery. The ignition temperature of grain dust, whether in the form of an aerosol or an aerogel, could be attained from heat sources such as exhaust systems, bearings or severely slipping

V-belts. Static electricity was shown not to be present normally.

Although no literature that discussed dust explosions in livestock production units could be located, a logical extension of Nawrocki's findings (82) suggests that a fire hazard could exist in any grain-dust laden atmosphere. Bundy and Hazen (16) report that the usual source of the dust in pig barns is either directly or indirectly traceable to the feed. Thus, a dusty pig barn could have the potential to be a fire hazard.

2.10 Dust and Odour.

Most of the odours coming from livestock production units are associated with the biological degradation of the animal wastes and the body odour of the animals. The primary atmospheric malodorous substances in pig and poultry houses are hydrogen sulfide (H_2S), ammonia (NH_3), aliphatic aldehydes, mercaptans and amines (12,18).

Lebeda and Day (66) found that particulate matter collected from the atmosphere of a pig confinement building was odoriferous. Eby and Willson (39) noted that the odours coming from a poultry house were intimately associated with the particulate matter in the atmosphere. In fact, filtration of the strong-odored exhaust air from a poultry house through plastic-foam removed all the components of poultry odours except ammonia. However, Willson (118) concluded in a later study that no direct relationship existed between dust and odour. He considered the problem of dust removal from poultry houses not as important as the odour-removal problem. Burnett (19) obtained results similar to those of Eby and Willson (39). Gas chromatographic analyses of the volatiles carried by the particulates composing poultry dust indicated the presence of individually odoriferous compounds. No one compound represented the typical poultry house odour. In addition, Burnett (18) found that particulates form a retentive source of odours.

Although the odour intensity within a piggery is primarily dependent on the efficiency of the ventilation and the waste disposal systems, Gordon (46) pointed out some extraneous factors which influence odour intensity. These include the animal density in the pen, the extent of the diffusion and mixing between the incoming air and that already in the pen, the degree of stratification in the atmosphere, the odour absorbability of materials in the pen, the extent of chemical union between vapours to form less odoriferous substances, the relative humidity, the amount of volumetric air space per animal, the habits of the animals and the floor gradient. Baxter (12) also considered most of these factors to influence the dust and bacterial content of the atmosphere within a confined animal production unit. Gordon (46) concluded that frequency of ventilation (air-changes per hour) was the more important consideration in controlling odour intensity than was ventilating volume (cubic feet of air per hour).

Abercrombie (1) used a five-person odour panel to investigate odour control in pig barns. Odour was associated with both the settled dust particles collected by a vacuum cleaner and the air-borne dust particles collected by an electrostatic process. The fraction of the particulate material between five and twenty microns in size seemed to be the most important particle-size range responsible for transporting obnoxious odours. Filtering the dust from the air could remove completely the odours carried in an air-stream. Although an activated carbon filter was found to be the most satisfactory, a wet washer was recommended as sufficient for practical use in a pig barn.

Odour control can be accomplished by masking an undesirable odour with a desirable odour, frequent waste removal, ventilation, filtration, washing or scrubbing the air with water sprays, aerosol disinfection, soil filtration, and chemical treatments (20,21,39,46,118). The similarity between some of the processes that are claimed to remove either dust or odour from the atmosphere suggests that an association exists between the two.

2.11 Dust and Micro-organism Concentrations in Animal Environments.

Many researchers studying in different areas have measured the dust and micro-organism concentrations in numerous animal environments and for varying purposes. Generally, these concentration data show little or no consistency with one another. Difficulties exist in making valid comparisons in the literature due to the impossibility of converting the different solids-loading units, as discussed in Section 2.5.11, the lack of standard measurement techniques, and the inability to compare quantitatively the different sampling devices discussed in Sections 2.6 and 2.7. However, this section presents a summary of the conclusions drawn by various researchers as well as the dust and micro-organism concentrations recorded for different animal environments.

2.11.1 Poultry.

Gentry et al (43) found the Andersen sampler (3) a reliable tool for the evaluation of hatchery sanitation. The sampler was much more sensitive than open plates subjected to sedimentation for the same period of time. In samples taken from four hatcheries, the number of organisms per one half of one cubic foot of air ranged from 0 to 1565 for bacteria and from 0 to 42 for fungi.

Reed and White (92) reported the results of research related to the performance of an air-washer in a poultry house. The dust-removal efficiency of the air-washer increased linearly from 74 to 89 percent as the water-pressure to the spray nozzles was increased from 20 to 50 pounds per square inch (gauge). Dust-removal efficiency was calculated on a weight basis.

Counts of 200,000 to 800,000 coliforms per gram in samples of settled dust from broiler houses were recorded by Harry (52). Lower counts ranging from 250 to 2500 per gram were obtained from brooder and battery houses. In the majority of samples, *Escherichia coli* was the predominating coliform present.

Dust problems in laying-hen and broiler environments were studied separately in replicated treatments by Grub et al (50). Airborne dust was collected on filters and dust concentrations determined by weighing. Caged layers produced the least amount of dust - 54 milligrams per bird-day. Birds on shavings produced from four to twelve times as much depending on the age of the litter. Some of the conclusions were as follows. (i) Poultry dust originated from feather and skin debris, feed, and litter. (ii) Temperature did not affect the production of dust by broilers raised on wire. (iii) Dust production by broilers on litter and raised at 90 degrees Fahrenheit dropped during the seventh and eighth weeks. (iv) Caged laying hens produced more dust in the temperature range of 60 to 70 degrees Fahrenheit than at either higher or lower temperatures. (v) More dust was produced by layers on litter during periods of illumination than during periods of darkness. (vi) Dust production from the litter increased with the age of the litter. (vii) Some airborne dust settled and returned to the litter. The comparison of atmospheric dust concentrations, by weight, for different litter materials reflected the type and density of each particular litter material and for this reason was considered misleading.

Anderson et al (4) undertook a study to determine what effects a short-term exposure to poultry-house dust might have on chickens subsequently exposed to a respiratory infection initiated by an aerosol of Newcastle disease virus. Large quantities of poultry-house dust were collected for use in exposing birds to an artificially-created dust atmosphere in an environmental chamber. Dust concentrations ranged from 0.025 to 1.16 milligrams per cubic foot of air and from 10,000 to 1,000,000 particles per cubic foot. These range limits did not correspond to the same time of sampling. The percentage of airborne particles less than 10 microns in diameter ranged from 25 while the birds were active to 50 when the birds were at rest. Many factors affected dust concentration including age and density of the bird population, ventilation rate, relative humidity, temperature, moisture content of litter, type of litter and the operation of feeding equipment (4). No significant differences were found between the mean death times or the percent mortality of birds exposed either artificially to dust alone or naturally to dust, ammonia and carbon dioxide prior to exposure to the aerosol of Newcastle disease virus, and control birds receiving the aerosol virus only.

Air sampling was conducted by Carlson and Whenham (24) to determine the bacteria and coliform concentration in broiler houses during the nine-week growing period. Concentrations were determined in units of numbers per cubic feet of air. The coliform count rose steeply from zero on the first day, reached a maximum of 33 between two and one-half and three weeks, dropped sharply to eight at about six weeks, and rose slowly to 30 at nine weeks. The total bacteria count began at zero, rose gradually to an average of 360,000 at about six weeks, and levelled-off at approximately 200,000 at nine weeks. An outbreak of septicemia developed about one week after the coliform count peaked.

Wolfe et al (119) subjected turkeys to two levels of atmospheric dust and ammonia. The experimental procedure was the same as that of Anderson et al (4,5). Dust was produced artificially at a low level ranging from 0.2 to 0.6 milligrams per cubic foot of air and at a high level ranging from 0.7 to 1.0 milligrams per cubic foot. Increasing the dust concentration from the low level to the high level resulted in more than double the rate of airsacculitis disease. No effect of ammonia on airsacculitis was detected. Interaction between dust and ammonia was not significant. Mortality rates and feed conversion of the turkeys were not affected by the dust and ammonia treatments. Adverse histopathological changes occurred in the respiratory system of turkeys exposed to the high dust and ammonia concentrations.

Burnett (19) determined the concentrations of airborne particulate matter in a high-density poultry house and studied the role of particulate matter as an odour-transport mechanism. Dust concentrations in a commercial poultry house with liquid manure handling ranged from 0.060 to 0.124 with an average of 0.093 milligrams per cubic foot of air.

2.11.2 Cattle.

Asaj (9) studied the number of micro-organisms settling from the air per minute on a square meter in mixed livestock (cattle and horses) stables. He concluded that the number of germs in stable-air was directly proportional to temperature, the mean temperature of irradiation and absolute humidity, but inversely proportional to better illumination and greater air circulation. The micro-organism concentrations ranged from 2,388 to 203,332 germs per square meter per minute.

An aerobiological survey of spore concentrations in an open cattle shed was conducted by Sreeramulu (106). Table 1 summarizes the data. The concentration of spores indicated a diurnal periodicity. Spores were suspected of an association with respiratory mycoses and other allergic diseases of both farmers and cattle.

TABLE 1: ATMOSPHERIC SPORE CONCENTRATIONS IN A CATTLE SHED (106).

Spore Group	Percentage of total catch	Daily Mean	Highest Concentration	Peak Mean	Time of daily peak (2400 hour day)
		(number of spores/cubic meter of air)			
Cladosporium	48.3	1350	16,280	2900	1000
Fusarium	27.0	750	6,920	1980	0400
Basiodospores	8.3	230	3,880	730	0600
Aspergilli	3.2	90	2,560	200	1800
Fragments of hyphae	3.4		800		1800
Others	9.8	270	3,000	550	1800

Spore concentrations of as many as 1,600 million per cubic meter of air in cowsheds while hay was being shaken were recorded by Lacey and Lacey (64). The concentration decreased by ninety percent in twenty minutes. Actinomycete spores, which are important in the etiology of farmers' lung disease and also may be a factor contributing to respiratory disease in livestock, formed up to ninety-eight percent of the total number of spores.

Westing et al (114) measured the amount of particulate matter in the air around cattle feedlots. The dust level for each feedlot was calculated as the downwind measurement minus the upwind measurement. The minimum, maximum and average feedlot airborne particle concentrations in micrograms per cubic meter were 53.7, 1268 and 628, respectively.

2.11.3 Pigs.

Gordon (47,48) investigated the bacterial state of the air in a number of piggeries at different times and under different management conditions. The number of bacterial colonies ranged from 54 to 30,780 per cubic foot of air when using a slit-sampler and from 34 to 8,808 per minute as counted from open petri dishes. The air-flow rate through the slit-sampler was one cubic foot per minute. Gordon thus showed both the extent and the variation of the bacterial complement which can be found in piggeries. The number of bacterial colonies was least in the barns with the highest absolute humidity. However, the type of bacteria differed. Gordon implied that the high-temperature, high-humidity piggeries were beneficial to the health of pigs. Fiser (41) and Fiser et al (42) found that humidities greater than 85 percent created more rather than fewer problems. Micro-organism counts were reduced only when relative humidity was raised to more than 85 percent. They agreed with and accepted the hygienic standard of 250,000 micro-organisms per cubic meter of air as set by Hoffman and Richter (56) for pig barns using dry feed.

The objectives of studies by Lebeda (65), Lebeda and Day (66) and Lebeda et al (67) were to determine the concentrations of ammonia, hydrogen sulfide, carbon dioxide, sulfur dioxide, and airborne bacteria within a pig confinement building with a fluid waste-handling system and to relate the concentration of gases to the management, ventilation, and structural parameters of the building. There was no significant difference in the number of airborne organisms present in the morning and the afternoon. The average number of micro-organisms was 4,800 per cubic foot of air.

Kovacs et al (62), in studying the influence of closed fattening pens on the production and health of pigs, found 80 to 95 dust particles per cubic centimeter of air. The diameters of 75 to 80 percent of these particles were from two to five microns. The dust was derived from dry-fed feed. During winter, 870 to 970 aerobic micro-organisms per liter of air were recorded. The micro-flora of the air was identical to that of the feed. In another study, Kovacs et al (62) examined the dust, micro-organisms, gases and their harmful effects on enclosed piggeries. Farrowing pens in the morning contained from 160 to 170 dust particles and from 1700 to 1950 micro-organisms per milliliter of air. The source of this contamination was mainly the bedding-straw. In the winter, piggeries with automatically-fed dry feed contained 110 to 430 dust particles per milliliter of air and 550 to 1600 micro-organisms per liter of air. The diameters of 90 to 95 percent of the dust particles were in the range of 0.5 to 2.0 microns. The micro-organisms in the air were predominantly saprophytic bacteria, mould-fungi and facultative pathogenic bacteria which belong to the normal micro-flora of the respiratory and digestive system. The hygienic implications resulting from this work were discussed previously in Section 2.8.2.3.

Fiser et al (42) conducted microbiological determinations of the atmosphere of piggeries. Micro-organism concentrations ranged from 44 to 1840 for a three-liter sample of air.

Martin (74) and Martin et al (75) studied the effects of sulfur dioxide and organic dust on the respiratory tract of pigs. Piglets were housed in a special chamber into which was blown mechanically-made corn or cornstarch dust. Dust samples were collected from within the chamber for weighing, sizing and counting of the particles. The dust measurement values were given as the mean plus or minus one standard deviation. The administered dust levels for the three experiments were; 220±135, 223±59, and 332±48 grams per day. The amounts of dust in the exposure chamber for the three experiments were; 6.02±1.44, 1.03±1.01, 0.827±1.03 milligrams per cubic foot of air. The number of dust particles per cubic foot of air for two exposures and the control were respectively: 283,930±33,408 for the particles larger than one micron, and 199,035 for particles larger than two microns; 1,249,100±434,600 for particles larger than 0.3 microns, and 58,290 for particles larger than two microns; and 1,276,300±547,400 for particles larger than 0.3 microns, and 35,200 for particles larger than two microns. The general conclusion reached was that there was no significant difference in the gross or histological appearance of lungs between the control and exposed pigs.

Doig (34) and Doig et al (35) using the same experimental procedure as that of Martin (74) studied the response of pigs to atmospheric ammonia and organic dust. Dust exposures were somewhat greater than those used by Martin (74). No significant effects were due to the dust exposure.

Frus, cited by Avey (10), evaluated dust concentrations within a pig laboratory. An average dust concentration of 0.74 grains per 1,000 cubic feet of air was reported. The airborne dust concentration tended to be proportional to the temperature and affected by feeding practices while no correlation could be found between dust levels and either relative humidity or animal age. The dust was composed of feed, powdered feces and litter.

Avey (10) evaluated the dust in a pig barn and its relation to heat exchanger application. Particle-size distributions for morning and afternoon dust samples, for all locations and for all three test days remained relatively constant. The approximate percentage distribution of dust particles within the selected size ranges were: 5 to 15 microns, 82; 15 to 25 microns, 13; 25 to 50 microns, 4; 50 to 100 microns, 0.5; and greater than 100 microns, 0.2 percent. The average dust concentration was 9,000 particles per liter of air. Gravimetric analysis established that the dust level from all samples varied between 18 to 72 milligrams per cubic meter of air. No relationship could be found between particle counts and weights of samples collected. Gravimetric dust concentration levels within the pig barn varied directly with relative humidity within the barn. Dust concentrations, by weight, were directly proportional to the barn temperatures. High dust concentrations were associated with increased animal activity. The effects of animal activity were thought to override even the effects of temperature and relative humidity on atmospheric dust concentrations. Animal activity was not carefully determined and, therefore, was not employed in the statistical analysis. The attempt to assess animal activity during sampling periods had the following basis; quiet - over 80 percent of the animals lying down; active - between 20 and 80 percent of the animals moving about; very active - over 80 percent of the animals moving about.

In an investigation of odour control for pig buildings, Abercrombie (1) found the average atmospheric dust concentration to be

7.44 milligrams per 1,000 cubic feet of air. The average particle-size distributions by percentage based on particle counts were: 60.9 greater than 5 microns, and 39.1 between 0.5 and 5 microns for atmospheric dust; and 68.25 greater than 5 microns, and 31.75 between 0.5 and 5 microns for settled dust. The unexpected high-percentage of finer particles, by count, in the settled dust compared to that in the airborne dust was considered to be due to the mechanical breakup of the settled dust during collection with a vacuum cleaner.

Bundy and Hazen (16) studied dust levels which could be associated with different feeding methods in pig confinement systems. The main conclusions were as follows. (i) The base dust level inside a confinement building could be predicted by measuring the outside dust level. (ii) Animal activity and dust levels were higher when the pigs were self-fed than when they were fed twice daily. (iii) The dust level was 50 to 75 percent less on concrete floors with floor-bedding than on stainless-steel slatted floors with self-feeders. (iv) There was no significant difference in dust levels between pellets and ground feed fed in self-feeders. (v) The dust level was less for floor-feeding of pellets than for floor-feeding of ground feed. (vi) Fifty percent of the dust measured was between 0.5 and 1.0 microns in size. (vii) Ninety-five percent of the dust in pig buildings was in particle-sizes considered to be damaging to the lungs.

The number of particles at the peak dust concentration levels, which corresponded to feeding times, was in the range of 1,500 to 4,000 per 0.01 cubic feet of air (16). The dust decay rates for floor feeding ranged from 15 to 45 minutes to reach the level that existed prior to feeding. The minimum dust level was reached 45 minutes to 90 minutes after feeding. The treatment of no-ventilation and no-circulation of air produced the highest dust levels across all particle-sizes. The various treatments with ventilation only and ventilation with circulation yielded the following approximate ranges of particle counts for the particle-sizes greater than or equal to the specified diameters (per 0.01 cubic feet of air); 1,000 to 6,500 for 0.5 microns, 500 to 4,000 for 1.0 micron, 300 to 2100 for 2.0 microns, 200 to 1,000 for 3.0 microns, and 100 to 900 for 5.0 microns.

Curtis et al (27) studied the effects of ammonia, hydrogen sulfide, and pig-barn dust, alone and combined, in the air on the performance and respiratory-tract health of otherwise healthy growing and finishing pigs. Pollutants were added to the ventilation air entering the exposure chambers. The dust used was collected from a commercial pig-finishing barn. Only when atmospheric dust was applied at a very high level (300 milligrams per cubic meter), was pig performance affected. No effects were observed at the dust levels (ten milligrams per cubic meter) more commonly encountered in practice. The results suggested that the performance of healthy pigs might not be affected by air pollution that is normal to enclosed pig shelters.

Bundy et al (17) studied the corona discharge, or ionization, method of dust control in pig-confinement buildings. After feeding, the normal minimum total number of dust particles greater than or equal to 0.5 microns ranged from 800 to 1,500 per 0.01 cubic feet of air. The conclusions drawn were as follows. (i) Ionization was most effective under zero-ventilation conditions. (ii) Ventilation was as effective as ionization for removing dust. (iii) Dust was collected more rapidly on a charged collector plate than on a neutral plate. (iv) More dust was collected on structural components when ionization was used. (v) The ceiling and walls should be charged so that dust particles could be directed to a specific surface that could be cleaned periodically.

2.11.4 Mixed Livestock.

Pechert (87) reported mean dust concentrations for a closed cattle barn, an open cattle barn, a finishing barn for pigs and a farrowing barn to be 6,670, 3,170, 12,740 and 31,290 dust particles per liter of air, respectively. The ratio of carbon dioxide and dust concentrations was found to range between 1:45 and 1:53 in barns. No linear correlation was found between dust particle concentration and relative humidity in the atmosphere of cattle or pig barns.

Both quantitative and qualitative examinations of the microflora (bacteria and fungi spores) existing in the atmosphere of dairy cattle and pig shelters during various activities were carried out by Negulescu et al (83). The micro-organism concentration in the atmosphere of dairy barns ranged from 90,000 to 150,000 per cubic meter for bacteria and from 2,100 to 3,400 per cubic meter for fungi spores. In the pig barns, the number of airborne bacteria was four to five times greater than in cattle barns, due mainly to the almost ceaseless activity of the pigs. The average number of fungi spores in the atmosphere of pig barns was 1,737 per cubic meter. In the qualitative examinations, the isolated bacteria were not pathogenic for white mice.

Dobie (33) determined atmospheric dust concentrations by weight for various agricultural environments. The average concentrations in units of pounds of dust per 24-hour day at a collection rate of 1,000 cubic feet of air per minute for the different sites were: poultry litter-house, 0.48; poultry cage-house, 0.12; dairy milking-parlours, 0.11; beef feeding-shed, 0.13; beef open-lot-feeding, 0.07; beef feedlot

0.22; sheep feeding-shed, 0.10; and dairy hay-feeding-manger, 0.84 pounds per day. Individual samples ranged from 0.03 to 0.84 pounds of dust per day. The main conclusion was that dust samples of agricultural environments showed great variation due to many variables such as animal activity, wind, wind direction, humidity, type of animal and housing, and sampling location.

Roller (97) stressed the need for study of the effects of air contaminants, including gases and dust, on equipment and animal performance. A more basic analysis of the environment within animal shelters was indicated as necessary.

The problems encountered in operating commercial cooling equipment in the severely dust-laden atmosphere of livestock structures were noted by Notestine and Pfost (84). Plugging, frequency of cleaning, and corrosion were the main problems. Littman (71) discussed the fitting of air-tempering and filtering equipment to animal-environment control. Good filtration was considered essential when recirculating air over the cooling and heating coils of such equipment installed in livestock buildings. The recommended filters were two-stage: the upstream one, a roll-type; the next, a moderate-efficiency, high-dust-holding capacity, renewable type.

Logsdon (72) summarized the characteristics and concentrations of dust in livestock shelters. Dust concentrations, by weight, in units of grains per 1,000 cubic feet of air for several livestock barns were: pigs, 0.62; pigs, 2.80; dairy cattle, 2.13; dairy cattle, 0.20; beef, 0.13; poultry, 0.95; and poultry, 0.86 grains per 1,000 cubic feet of air. A particle-size analysis (Figure 1) showed a very similar distribution for both the pig and dairy-cattle barns. The particle-size

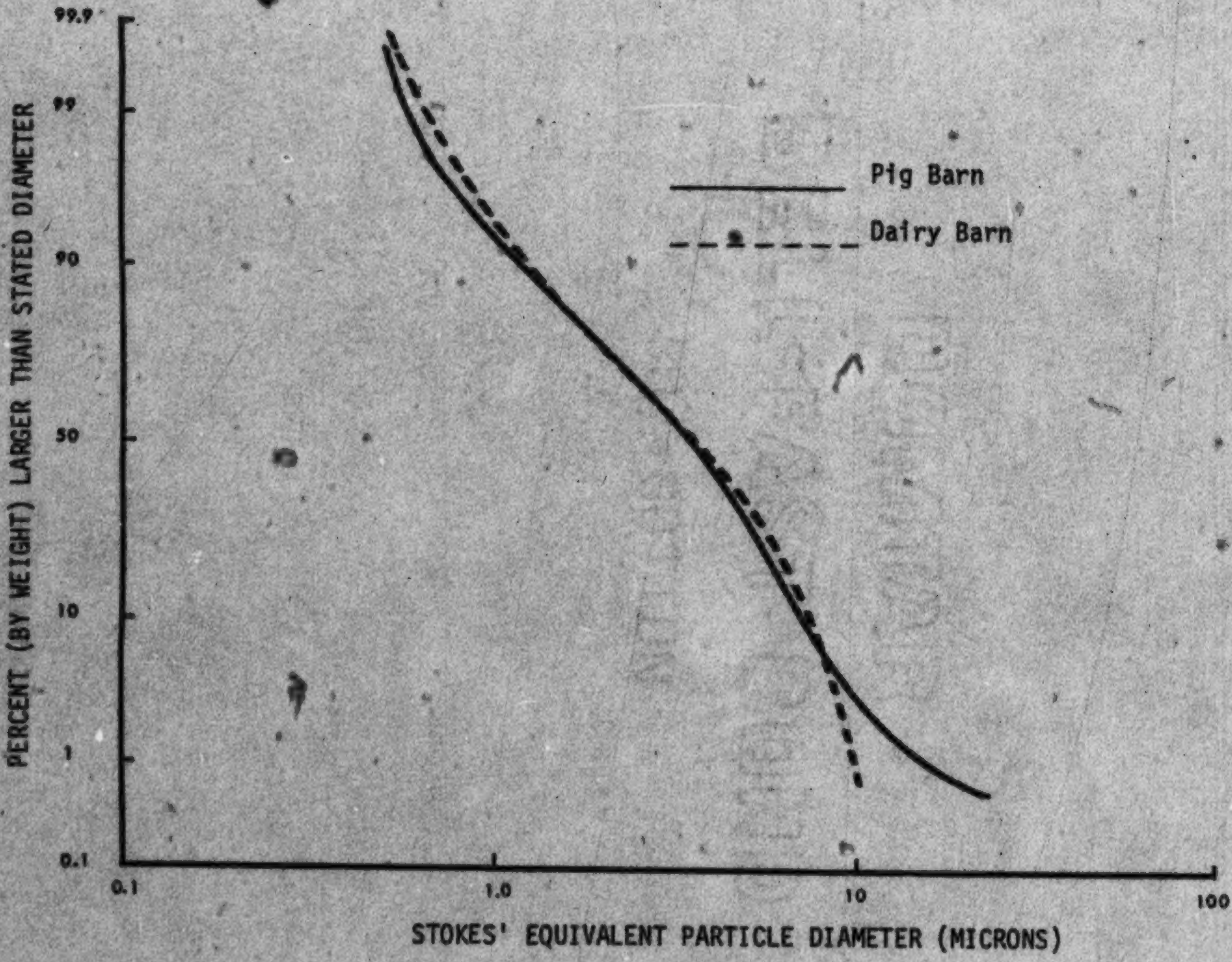

Figure 1. Particle-size distribution of dust from pig and dairy barns (72).

distribution compared favourably to that of an urban atmosphere; the median size being in the order of 3.0 to 3.5 microns. Filters suitable for protecting air-conditioning equipment could contribute greatly to bacterial control because of their ability to remove the atmospheric dust particles on which possibly a great number of bacteria are riding (72).

Gravimetric dust measurements in several livestock buildings were recorded by Hilliger (53,54). Dust concentrations varied widely and ranged from 3.4 to 25.7 milligrams per square decimeter per day. The feeding-method, the type of bedding and the rapidity of air currents had a considerable influence on the atmospheric dust concentrations. The animal species, temperature, relative humidity and season of the year were considered to show good agreement with other observations on dust particle concentrations in livestock buildings but varied considerably from findings for the outside air. The latter comment contradicts the findings reported by Logsdon (72). In another study, Hilliger (53,54) concluded that there was reason to believe that a constant relationship existed between the number of micro-organisms and the number of dust particles in livestock shelters. Table 2 presents the data from which this conclusion was drawn. Schonherr, as cited by Hilliger (53), found 65 to 667 dust particles per micro-organism in diary barns. Majweski, as cited by Hilliger (53), found an even greater range; up to 3,000 dust particles per micro-organism.

Figure 2 summarizes some of the atmospheric dust concentrations by weight that various researchers have found in different situations. A similar graphical presentation of atmospheric dust concentrations by count probably would have little meaning due to counts based on different size ranges, the variations resulting from the time of sampling, and the use of sampling instruments with different particle-size limits.

TABLE 2: DUST PARTICLE AND MICROORGANISM COUNTS IN LIVESTOCK BUILDINGS (53,54).

	Poultry house		Piggery	
	volumetric #/liter	sedimentation #/cm^{2}min	volumetric #/liter	sedimentation #/cm^{2}min
Dust				
minimum maximum	21,600 158,400	221 572	3800 16,300	30 199
average	57,934	396	8407	94
Microorganisms				
minimum maximum	2,200 16,200	5.9 21	1182 11,400	2.2 19.5
average	7,118	11.4	4789	10.5
Ratio of dust particles to one viable microorganism				
minimum maximum	4.1 14.8	25.7 68.5	0.6 3.7	4.6 25.3
average	9.4	39.0	2.6	11.3

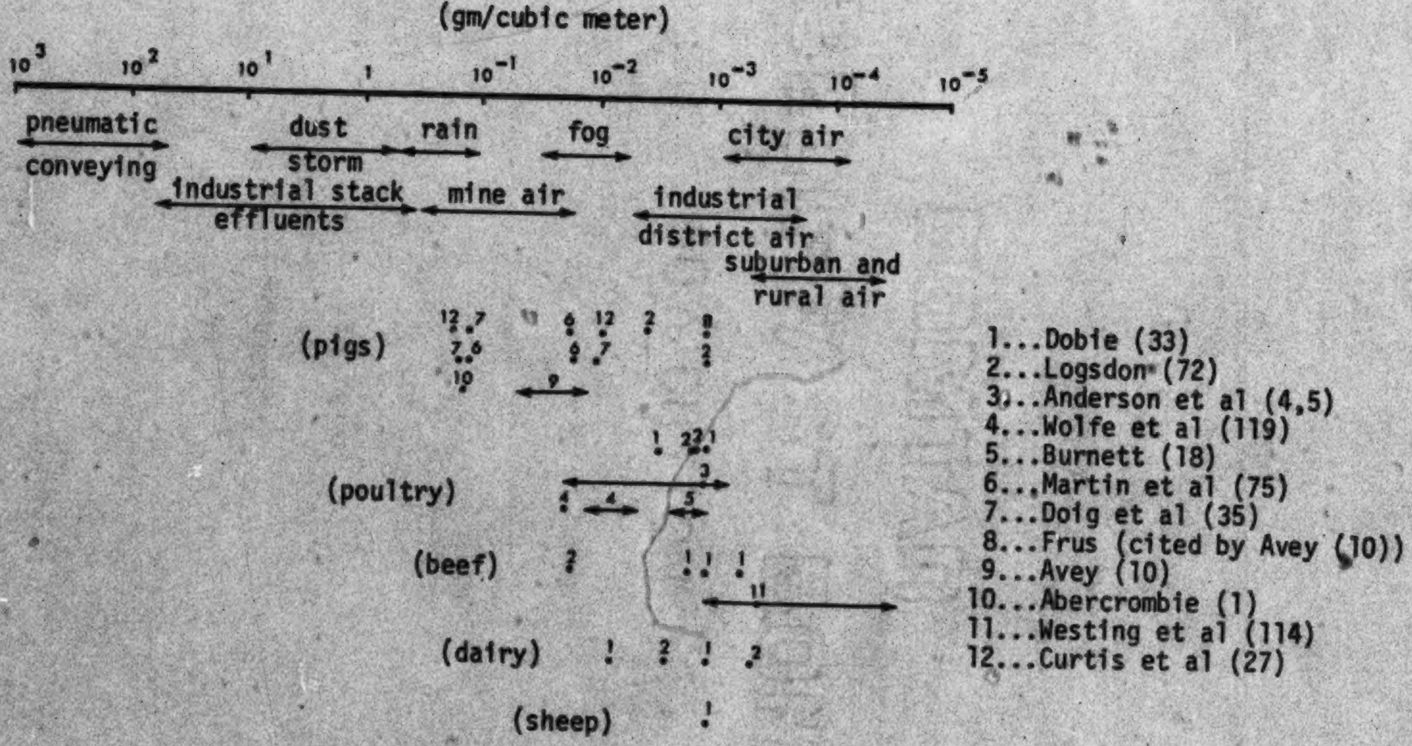

Figure 2. Atmospheric dust concentrations occurring in different situations.

3. EXPERIMENTAL PROCEDURE

3.1 Facilities.

The environmental chamber (Figures 3 and 4), Honey's Hog House, located at the Agricultural Engineering facilities at the Ellerslie Research Station of the University of Alberta was used for this research project. The inside dimensions of the completely enclosed chamber were about 20 feet in width, 30 feet in length and 10 feet in height. The environment in the chamber was conditioned somewhat by the use of equipment located in an adjoining mechanical room. Ventilation was provided by a fan drawing a constant volume (about 1500 cubic feet per minute) of filtered air from outdoors. The ventilation air was heated using hot-water-heat-transfer coils inside the ventilation duct. Water vapour was added to the ventilation air by a steam generator operating on the basis of a humidstat-controlled pressure differential. Ventilation air could be neither cooled nor dehumidified. The ventilation air entered the chamber through five equal-flow inlet ports equally spaced along the main duct (Figure 4) which runs the length of the chamber. The main duct was about seven feet above the floor. The ventilation air was exhausted from the chamber through two dampered exhaust openings equally spaced on the wall opposite the incoming air ports. These exhaust openings can be seen in Figure 3 in the front of the chamber.

Two equally spaced gutters partially extended across the width of the chamber floor. A third gutter met the others at right angles and ran the length of the chamber floor. The gutters of sloping depth were eight inches wide, covered with sections composed of small metal slats, and emptied into a manure storage pit about 200 feet away from the chamber. The chamber floor was smooth concrete, with about an inch fall per 30

Figure 3. An exterior view of the research barn.

Figure 4. An interior view of the research barn before construction of the four pig pens.

inch run sloping toward the gutters. Lighting was provided by incandescent ceiling fixtures. Steel roof trusses projected into the chamber and extended across the width of the chamber.

The author designed, supervised and assisted with the construction of four individual pig pens, each totally enclosed, inside the environmental chamber. The four pens are shown in Figures 5 and 6. All lumber used was construction grade spruce. All plywood used was three-quarter inch sheathing grade fir.

Two inch by four inch nominal-size lumber spaced at two foot centres were bolted to the steel roof trusses. These pieces of lumber ran the length of the research-barn roof and acted as top plates for the two inch by four inch nominal-size studs which formed the walls of the four pens. The bottom plates rested on the concrete floor and were held in place by short lengths of lumber butted against the chamber walls. Plywood was nailed to the stud walls on the inside of each pen as shown in Figure 7 to form a solid five foot high wall.

The inside dimensions of each pen were 6 feet wide and 13 feet long. Due to the gutter layout, the floor slope in each pen was diagonally across the pen toward the front. Therefore, the lowest part of each pen floor was at one of the front corners of the pen. A hinged door together with a drop-gate were constructed in the front of each pen. The longitudinal gutter was not located within the pens. About one and a half inches of each of the chamber-width gutters ran along the length of each pen. Figure 5 shows the gutter layout. Part of the gutters can be seen in Figures 4 and 6. The small amount of gutter actually in each pen coupled with the long distance to the manure-storage pit precluded the use of the gutter system for anything but the transport of

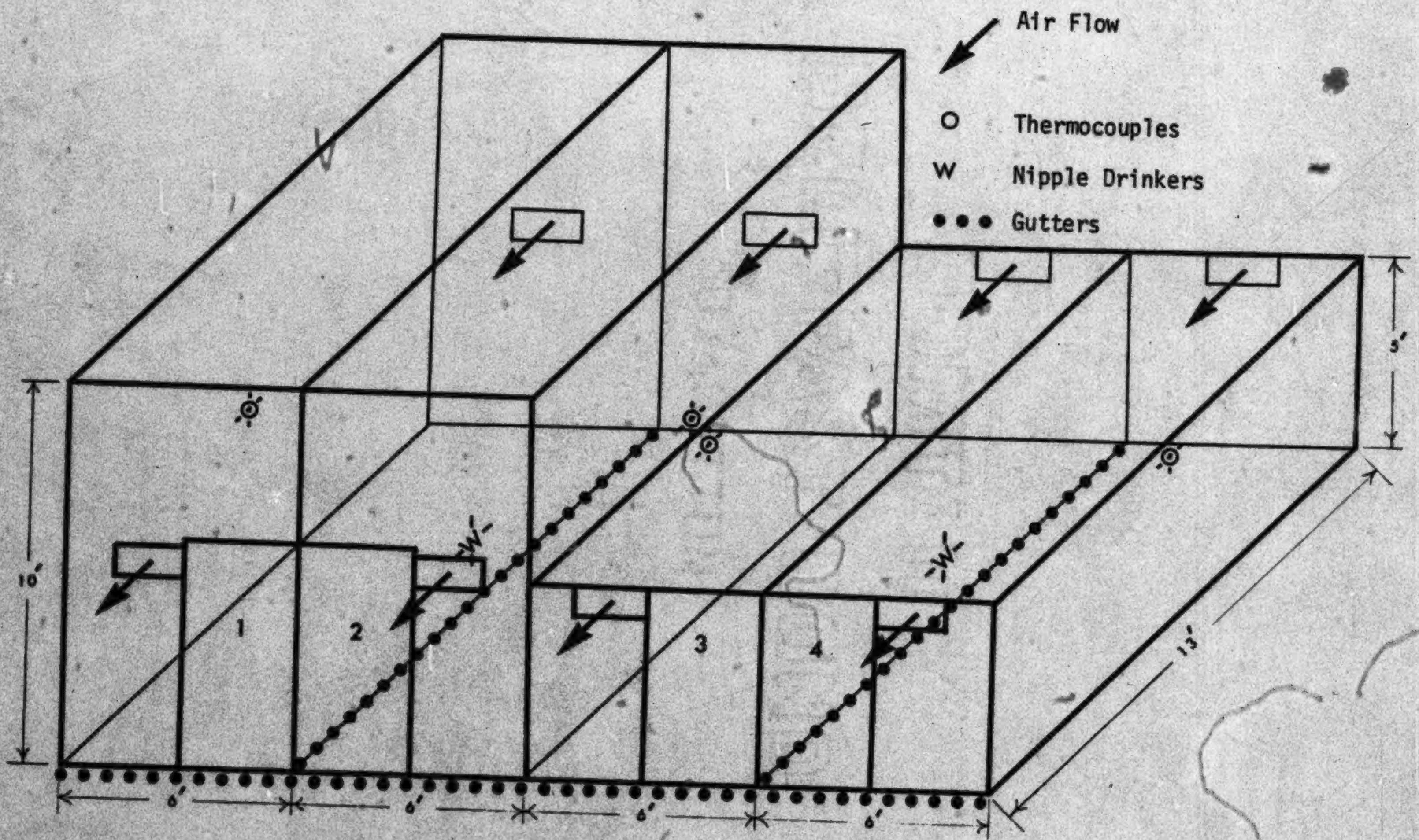
Air Flow
O Thermocouples
W Nipple Drinkers
● ● ● Gutters
1
2
3
4
W
W
10'
5'
13'
6'
6'
6'
6'

Figure 5. Sketch of four pig pens in research barn.

Figure 6. Front view of the four pig pens.

Figure 7. Inside view of a large volume pen.

fluid wastes containing little or no solids. In Figure 7, the gutter cannot be seen because it is plugged with excess feed and feces. This was a normal situation.

Two of the adjacent pens were built with five foot high ceilings while the remaining two adjacent pens were constructed with ten foot high ceilings. The ceiling heights of ten feet and five feet provided two pens with a volume of 780 cubic feet each and another two each with a volume of 390 cubic feet, respectively. Six-mil polyethylene film was used to form the ceiling and part of the walls down to the plywood. Each pen was caulked and taped to minimize air leaks.

Water was provided in each pen by one nipple drinker, as shown in Figure 7, located (Figure 5) midway along the length of each pen about 18 inches above the gutter.

Ventilation air entered the rear of each pen through an inlet port (9.25 inches by 22.25 inches) via a polyethylene duct attached to one of the five ports along the main duct. The ventilation air was exhausted from the front of each pen into the main air space of the building through exhaust ports of the same size as the inlet ports. The ventilation ports were located in the ends of each pen about midway across the width and five feet above the floor. Sliding gates over each of the four inlet ports and also over the fifth port of the main duct provided the control system used to vary and balance individual pen air-flow rates. Identical downward-directing baffles (Figure 7) were added to each of the pen-inlet ports to ensure adequate air mixing within the pens.

Four plywood self-feeders each capable of containing 150 pounds of dry feed were designed and built for the project. The self-feeders were later modified by the addition of lengths of chain to prevent the feed from bridging. An adjustable gate to control the flow of feed into the trough, and steel brackets in the trough to prevent the pigs from wasting feed were also added to each unit.

3.2 Experimental Design.

The primary dependent factor studied in this project was atmospheric dust concentration within each of four separate pig pens. Settled dust concentrations were also determined. Independent factors consisted of two pen volumes, two feeding methods, two levels of relative humidity and two levels of air-flow rate. These independent variables were chosen for investigation on the basis of the literature reviewed as they appeared to be factors most likely to affect atmospheric dust concentrations. The temperature was to remain constant. The same ten pigs remained in each pen for the duration of the experiment.

The two pen volumes, V_1 and V_2, were 780 and 390 cubic feet, respectively. The two feeding methods, F_1 and F_2, were floor-feeding twice daily and self-feeding, respectively. The two relative humidity levels, H_1 and H_2, were, respectively, the relative humidity occurring naturally within the pens and the relative humidity resulting (artificially) from the introduction of water vapour into the pens via the incoming ventilation air. The two levels of air-flow rate, Q_1 and Q_2, were 350 and 175 cubic feet per minute, respectively.

The four independent factors, each having two levels, yielded a total of sixteen possible combinations. Since there were two pens of each of the two volumes, the sixteen combinations were duplicated. This resulted in thirty-two treatment combinations. These were arranged in a split-plot factorial experimental design (120) so that an analysis of variance could be carried out on the dust concentration data. The smallest sub-plot was the pen. There were four independent pens available. The combinations of feeding systems and air-flow rates occurred within the pens. The relative humidity level was the same for all pens at the same time.

Eight treatment periods, T, were required in order to test all the treatment combinations. Two randomized four-by-four Latin squares composed of all combinations of feeding systems and air-flow rates were constructed. These Latin squares were inserted in the experimental design across the four pens and the four treatment periods, all at the same relative humidity level. The object in the use of the Latin squares was to minimize the effects, if any, between treatment periods. The two relative humidity levels were randomized in four blocks of two across the eight treatment periods in order that the effects, if any, between treatment periods be minimized. The treatment periods varied in length from eleven to three days depending on the amount of time taken to establish and stabilize the required treatment conditions. The experimental design is shown in Figure 8 along with the treatment nomenclature.

As a prelude to this project, and for possible use in it, a short study (57) was conducted by the author to determine an activity index for pigs. Other researchers have indicated that they suspect that animal activity is closely related to atmospheric dust concentrations (10,16). The analysis of the activity data for four observed pigs suggested the use of the daily resting pattern of the pigs as the basis for a pig-activity index. The daily resting pattern was used as an aid in determining the times for taking grab-samples of atmospheric dust.

Treatment period		V_1		V_2	
		Pen 1	Pen 2	Pen 3	Pen 4
T_1	H_1	F_2Q_2	F_2Q_1	F_1Q_2	F_1Q_1
T_2	H_2	F_2Q_1	F_1Q_2	F_1Q_1	F_2Q_2
T_3	H_1	F_1Q_2	F_1Q_1	F_2Q_2	F_2Q_1
T_4	H_2	F_1Q_2	F_1Q_1	F_2Q_2	F_2Q_1
T_5	H_2	F_1Q_1	F_2Q_2	F_2Q_1	F_1Q_2
T_6	H_1	F_1Q_1	F_2Q_2	F_2Q_1	F_1Q_2
T_7	H_1	F_2Q_1	F_1Q_2	F_1Q_1	F_2Q_2
T_8	H_2	F_2Q_2	F_2Q_1	F_1Q_2	F_1Q_1

TREATMENT NOMENCLATURE

V_1...pen volume, 780 cubic feet

V_2...pen volume, 390 cubic feet

H_1...relative humidity, natural (low)

H_2...relative humidity, artificial (high)

F_1...floor-fed

F_2...self-fed

Q_1...air flow rate, 350 cubic feet per minute

Q_2...air flow rate, 175 cubic feet per minute

Figure 8. Experimental design and treatment nomenclature.

The daily resting and activity pattern of the pigs in this dust project was similar to that of the pigs observed in the activity-index study. In order that any greatly exaggerated effects due to pig activity would be avoided, the atmospheric dust sampling times (1000 to 1200, 1300 to 1500 and 1600 to 1800 hours) were chosen to correspond to those times when the pigs would be spending about 60 percent of the time resting.

3.3 Pig Management.

Forty pigs of the white breeds, averaging 50.4 pounds live-weight, were obtained for the experiment through the Alberta Livestock Commission from the Edmonton Public Stockyards. The pigs were delivered to the Ellerslie Research Station on May 1, 1974. They consisted of eighteen gilts, fourteen barrows and eight young boars. In all likelihood, the pigs came from several different farms. No attempt was made to ascertain their history.

The day after their arrival, the pigs were numbered using an ear-notch system (Figure 9), innoculated with Erysipelas bactrin, and weighed. The eight young boars were castrated. Randomly chosen pigs from each of three groups; gilts, barrows, and barrows castrated on arrival, were allotted to each of the four experimental pens in as equal numbers as possible. Each pen contained ten pigs. The random selection of the pigs and the approximate balancing of the number of pigs from each sex-group in each pen was an attempt to eliminate the effects, if any, of sex on dust concentrations.

The pigs were fed from self-feeders for an acclimatization period of two weeks. Commercial feeds were used throughout the experiment, with a 16 percent protein grower ration being fed up to 100 pounds live-weight and a 15 percent protein grower-finisher ration fed

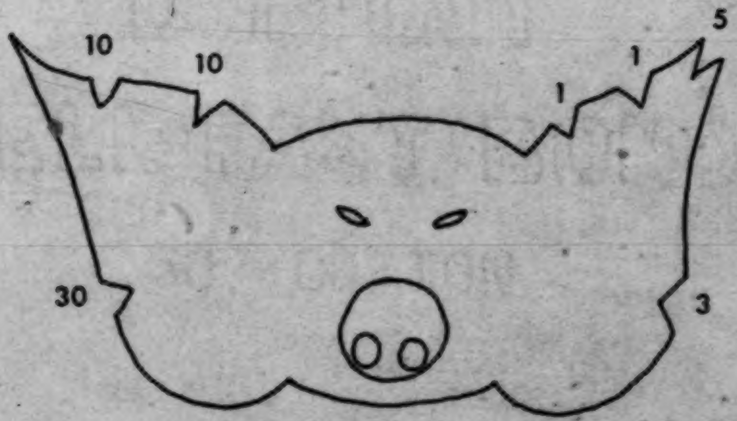
10
10
1
1
5
30
3

Figure 9. Pig ear notches representing consecutive numbers (1 to 59).

thereafter. Table 3 gives the feed analysis as stated by the manufacturer. The modulus of fineness and the modulus of uniformity of the feeds were determined in accordance with the American Society of Agricultural Engineers standard sieve analysis procedures (51). The feed was oven-dried at 212 degrees Fahrenheit for 24 hours. Sieve analyses were conducted using United States Standard Sieves (numbers 8,16,30,50, and 100) with an automatic sieve shaker.* Sieving time was five minutes. Tables 4 and 5 present data relative to these determinations.

The modulus of uniformity for both the grower and the grower-finisher ration was 0:6:4 corresponding to the coarse, medium and fine fractions of the feed. The modulii of fineness for the grower and the grower-finisher were 2.44 and 2.48, respectively.

The pigs were weighed approximately every two weeks. Figure 10 presents a graph of the average pig weight per pen plotted against time for the duration of the experiment. Average pig weights per treatment (Appendix C, Table C1) were based on the straight-line interpolation of the average pig weight per pen between consecutive weigh days. The intersection of the midpoint of each treatment period with the linear graph (Figure 10) of pig weight plotted against time was assumed to be the average pig weight for each treatment.

The lights in the research barn remained on throughout the day during the experiment.

The experiment had to be interrupted when two of the pigs

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* Syntron, model TSS-31B, Syntron Company, Homer City, Pennsylvania, U.S.A.

TABLE 3: FEED ANALYSIS.

16% Hog Grower (Unifeed 403)*

Crude Protein (min.) 16.0%

Crude Fat (min.) 2.5%

Crude Fibre (max.) 6.0%

Salt (actual) 0.5%

Calcium (actual) 0.7%

Phosphorous (actual) 0.55%

Zinc (actual) 0.011%

Vitamin A (min.) 2000 I.U. per lb.

15% Hog Gro-finisher (Unifeed 406)*

Crude Protein (min.) 15.0%

Crude Fat (min.) 2.2%

Crude Fibre (max.) 7.0%

Calcium (actual) 0.65%

Phosphorous (actual) 0.55%

Salt (actual) 0.5%

Zinc 0.011%

Vitamin A (min.) 1500 I.U. per lb.

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* United Feeds Limited, Calgary, Alberta.

TABLE 4: CALCULATION OF MODULUS OF FINENESS OF PIG FEEDS USED.*

Screen mesh	Percent of material on each screen (3 samples, 100 gms. each)			
				16% Hog Grower
8	0.21	x5	=	1.05
16	18.4	x4	=	73.6
30	36.2	x3	=	108.6
50	23.2	x2	=	46.4
100	13.9	x1	=	13.9
pan	8.09	x0	=	0.0
	100.0			243.55
Modulus of fineness (243.55/100) = 2.44				
				15% Hog Gro-finisher
8	0.30	x5	=	1.5
16	17.4	x4	=	69.6
30	39.6	x3	=	118.8
50	23.0	x2	=	46.
100	12.4	x1	=	12.4
pan	7.30	x0	=	0.0
	100.0			248.3
Modulus of fineness (248.3/100) = 2.48				

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* based on A.S.A.E. R246.1 (51).

TABLE 5: CALCULATION OF MODULUS OF UNIFORMITY OF PIG FEED USED.*

Screen mesh	Percent of material on each screen (3 samples, 250 gms. each)				
		16% Hog Grower			
	coarse				
8	0.392	0.392/10	=	0.039	0
	medium				
16	19.4				
30	40.5				
	59.9	59.9/10	=	5.99	6
	fine				
50	22.5				
100	11.8				
pan	5.4				
	39.7	39.7/10	=	3.97	4
Modulus of uniformity = 0:6:4					
		15% Hog Gro-finisher			
	coarse				
8	0.291	0.291/10	=	0.029	0
	medium				
16	19.2				
30	37.8				
	57.0	57.0/10	=	5.7	6
	fine				
50	22.6				
100	12.95				
pan	7.2				
	42.75	42.75/10	=	4.275	4
Modulus of uniformity = 0:6:4					

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* based on A.S.A.E. R246.1 (51).

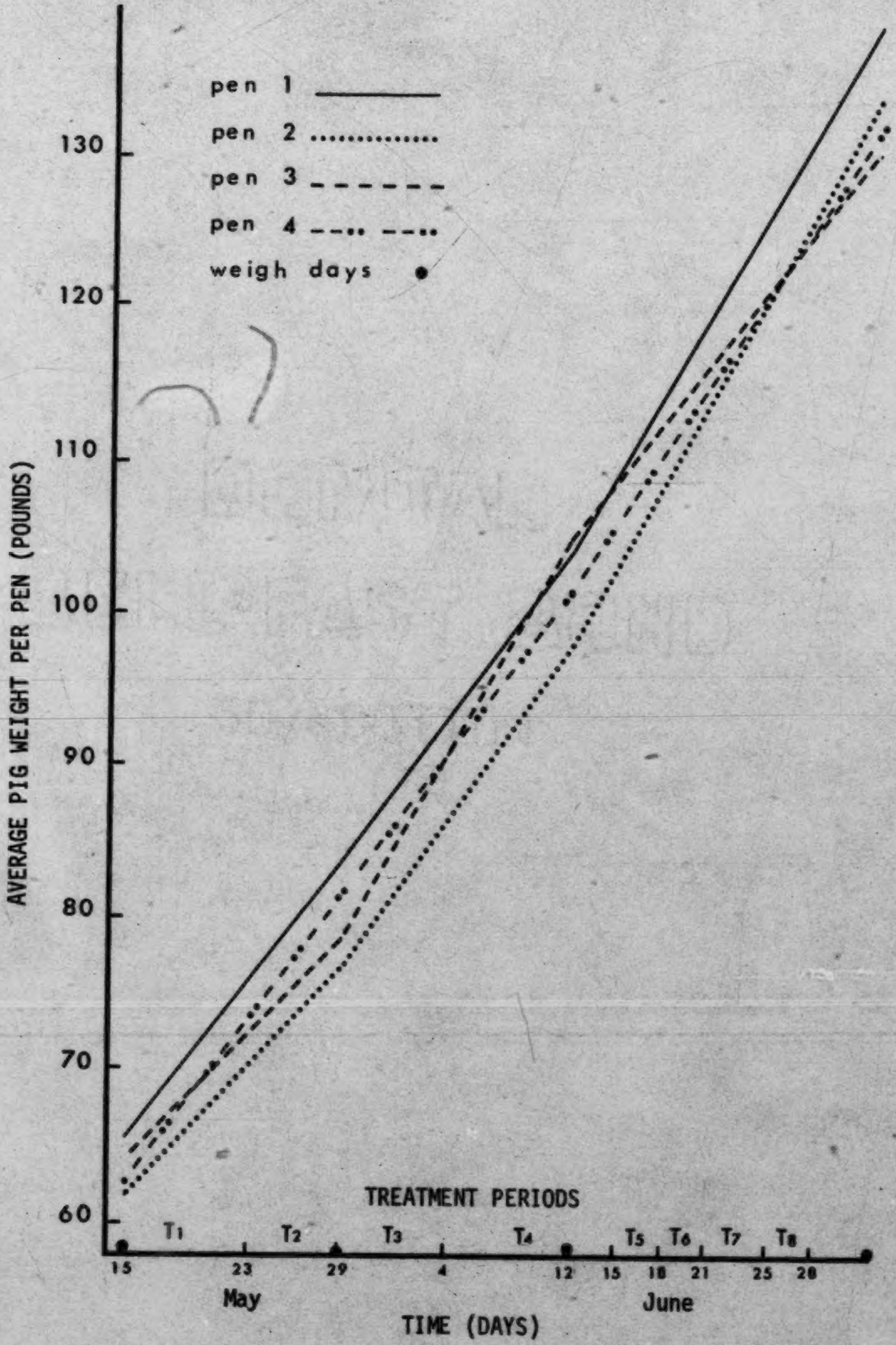

Figure 10. Average pig weight per pen during treatment periods.

became ill with a form of dysentry and were removed from the treatment pens. The sick pigs were treated with chloramphenicol and combiotic. One pig recovered but the other died. A replacement pig of about the same size and weight as the remaining pigs was obtained from a local pig farmer. This new pig along with the recuperated pig was added to the treatment pens and allowed to acclimatize before the experiment was resumed.

The pigs were given a minimum two-day acclimatization period between treatments. This period seemed quite adequate. The pigs did not indicate any stress when changing from one treatment to another.

There seemed to be a relatively high incidence of lameness among the pigs throughout the experiment. This was probably due to the fact that the smooth concrete floor became extremely slippery when wet.

Water was available to the pigs at all times. The feeding area in each pen was directly across from the drinker (Figures 5 and 7). Self-feeders were filled as required to keep a constant supply of feed available to the pigs on that treatment. Floor-feeding was carried out daily at about 0900 and 1500 hours. Daily feed requirements for floor-feeding were based on the recommendations given in Table 6 (110). Feed consumption was determined by weighing all feed entering the pens. The self-feeders were removed from the pens during floor-feeding treatment periods.

All the pigs were returned to the self-feeding method at the end of the eighth and final treatment period, and fed to a finished live-weight of about 180 pounds before being shipped to a local meat-packing plant. The pigs were delivered in three batches containing twenty-one, twelve and seven animals. The final batch of seven pigs

TABLE 6: PIG FEED REQUIREMENTS (110).

Pig Weight (pounds)	Daily Feed Intake (pounds)
50	3.0
60	3.4
70	3.7
80	4.6
90	5.5
100	5.7
120	6.0
140	7.1
160	7.3
180	7.5
200	7.8

contained several unfinished, or light, pigs with resulting low quality grades. The carcass quality is included in a summary of pig data presented in Table 7. A data sheet, a sample of which is shown in Appendix A, Figure A1, was used to record the original data concerning the pigs.

The solid manure was removed manually from the pens three times weekly during the experiment. Between treatments, the pigs were removed from each pen while the ceiling, floor and walls of the pen were hosed down with water. This cleaning procedure eliminated the effects, if any, on treatments due to dust recirculating from a continuous build-up of settled dust inside the pens (90).

3.4 Instrumentation and Data Collection.

This research project required the measurement of temperature, air-flow rate, relative humidity, atmospheric dust concentration, settled dust concentration, pig weight and feed consumption. Pen number and pen volume were fixed and were discussed in Section 3.1. Pig numbers, pig weights and feed consumption were discussed in Section 3.3.

3.4.1 Temperature and Relative Humidity.

Temperature and relative humidity were determined using type J copper-constantan thermocouples. A wet-bulb and a dry-bulb thermocouple were located midway along the length of one side of each pen about five feet above the floor as previously shown (Figure 5). The thermocouple junctions (temperature measuring points) were located (Figure 11) in the range of two to six inches from the pen wall. The wet-bulb thermocouples were covered for about two inches by one end of a standard psychrometric sock, the other end of which extended into a plastic jar containing water. The thermo-electromotive force of each thermocouple was continuously

TABLE 7: SUMMARY OF PIG DATA.

Pig #	Sex	Starting weight	Finishing weight	Average total feed input/pig (pounds)	Carcass quality (index)
		(pounds)			
2	g	54	175*		100.2
3	bc	51	195*		100.2
18	g	52	160s		98
23	g	55	180*		100.2
30	bc	53	200*		100.2
31	b	47	170*		100.2
34	b	49	180x		87L
35	g	54	165x		103
36	b	49	160x		98
40	b	52	180*		100.2
Average of pen # 1		51.6	176.5	461.4	98.7
4	bc	50	185*		100.2
12	bc	49	160x		98
15	b	44	185*		100.2
21	g	47	170x		98
24	b	46	165x		98
25	b	50	160x		100
26	b	51	185*		100.2
28	g	55	190*		100.2
29	g	40	150s		87L
39	g	45	180*		100.2
Average of pen # 2		47.7	173	459.5	98.2
1	b	57	180*		100.2
8	bc	56	200*		100.2
9	g	46	180*		100.2
11	g	50	175*		100.2
13	g	50	145s		87L
16	b	48	145s		87L
17+	b	48	190*		100.2
20	bc	56	200*		100.2
22	g	52	155x		87L
32	g	48	165x		100
Average of pen #3		51.1	173.5	419.1	96.2

Continued

TABLE 7: SUMMARY OF PIG DATA (Continued)

Pig #	Sex	Starting weight (pounds)	Finishing weight (pounds)	Average total feed input/pig (pounds)	Carcass quality (index)
5	g	51	160s		87L
6	g	55	165*		100.2
7	bc	59	190*		100.2
10	b	48	175x		100
14	b	46	150x		87L
19	bc	55	185*		100.2
27	g	55	185s		103
33	g	46	145s		87L
37	g	47	170*		100.2
38	b	50	180x		102
Average of pen # 4		51.2	170.5	456.9	96.7
Average of all pens		50.4	173.4	449.2	97.4

g...gilt
b...barrow
bc..barrow, castrated on arrival
+...replaced by pig #67
*...shipped 25/7/74
x...shipped 1/8/74
s...shipped 8/8/74
L...light carcass weight, less than 125 pounds

Note: pigs shipped 25/7/74 were given as an average carcass quality (not individually graded as requested).

Figure 11. Thermocouple junctions.

recorded on paper as temperature in degrees Fahrenheit. The recording machine used was a 24-point thermocouple recorder* (Figure 12), automatically employing a constantly balancing and compensating circuit. The thermocouple recorder was calibrated for the range from zero degrees Fahrenheit to 100 degrees Fahrenheit using a manually balanced potentiometer which was set according to tabular values of thermo-electromative force for copper-constantan thermocouples. Although the recorder had the capability of operating continuously, only the temperatures coinciding with sampling times were recorded.

The calibration of each of the eight individual thermocouples employed in this experiment is discussed in Appendix B. The resulting calibration equations ([B4] to [B11]) were used to determine actual temperatures from the recorded temperature readings. Appendix C, Table C9, contains the average corrected pen temperatures for each treatment at the time of sampling.

Relative humidities were determined by entering a psychrometric chart** with the corrected dry-bulb temperatures and the corresponding corrected wet-bulb temperatures. Appendix C, Table C11, contains the average relative humidities, for each treatment, measured during atmospheric dust sampling.

3.4.2 Air-Flow Rate.

A rotating vane anemometer*** (Figure 13) was used to measure

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* Honeywell, Electronik 15 Strip Chart Multipoint Recorder.

** Normal Temperature Psychrometric Chart, Carrier Corporation.

*** Airflow Developments Limited, Lancaster Road, High Wycombe, England.

Figure 12. Thermocouple recorder.

Figure 13. Rotating vane anemometer.

the velocity of the air exhausted from the pens. Knowing both the cross-sectional area, A, of an exhaust port and a correction factor, K, applicable to anemometer air-flow rate measurement, as well as the anemometer-measured air velocity, S, allowed the air-flow rate, Q, to be calculated from the following equation (59):

$$Q = S \times A \times K \qquad [1]$$

Table 8 shows the calculation of the air velocities, S_1 and S_2, required to obtain the desired high, Q_1, and low, Q_2, air-flow rates of 350 and 175 cubic feet per minute, respectively. S_1 and S_2 correspond to Q_1 and Q_2, respectively. The magnitudes of the air-flow rates were chosen so that as much as possible of the air moved by the fixed-flow fan which supplied the research facility with fresh air would be provided to ventilate the pig pens. Due to the difficulty of balancing the air-flow rates between the pens, the actual high air-flow rate, Q_1, was 358 cubic feet per minute while the actual low air-flow rate, Q_2, was 175 cubic feet per minute.

3.4.3 Atmospheric Dust Concentration.

An Andersen air sampler (Figures 14 and 15) was used to obtain grab-samples of atmospheric dust concentrations. The Andersen air sampler is a six-stage cascade impactor (3), the operation of which was discussed previously (Section 2.6.6). The sampling rate of the sampler was 1.0 cubic foot of air per minute. The circular dust collection plates used in this experiment were glass. The sampler was calibrated using an aerosol acrylic which, according to Andersen (3), has a specific gravity of 1.0 and forms spherical particles throughout the normal size-range of atmospheric dust particles. A cloud of aerosol acrylic was sampled and the acrylic particles which impacted on the glass plates subjected to

TABLE 8: CALCULATION OF REQUIRED AIR VELOCITIES.

Q_1 = 350 cfm

Q_2 = 175 cfm

A = (9.25 x 22.25)/144 - 1.43 square feet

K_1 = 8.808

K_2 = 0.762

From Q = S x A x K [1]

S_1 = 303 fpm

S_2 = 161 fpm

Figure 14. Andersen air sampler.

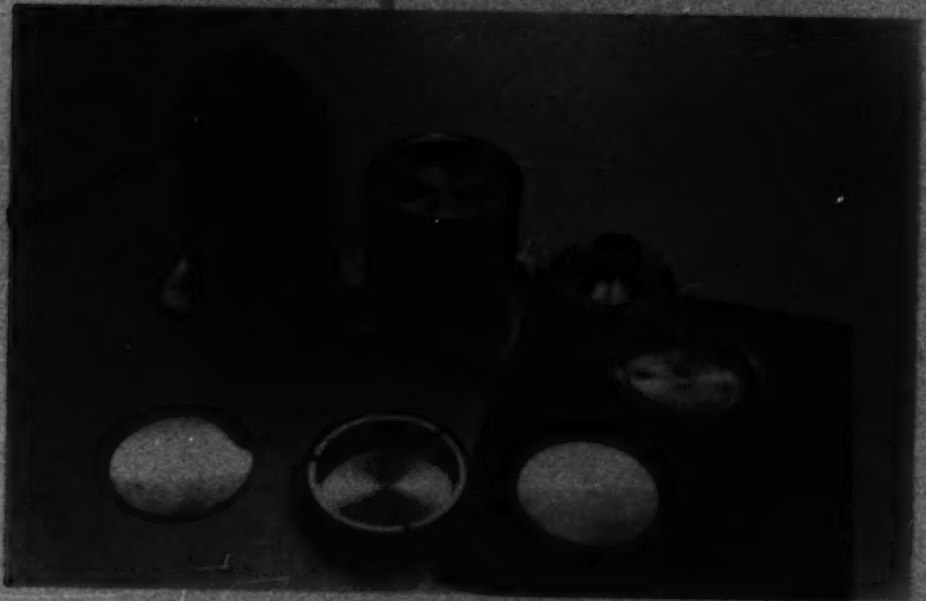

Figure 15. Andersen air sampler, partially dismantled.

microscopic analysis.

The microscope* employed in this experiment is shown in Figure 16. A stage micrometer** was then used to measure the sizes of the aerosol acrylic particles on each of the six glass-plate stages of the sampler. The resulting size range for each of the six stages (Figure 17) contained about 80 percent by count of all the impacted particles. This method of calibrating particle-size ranges is based on the aerodynamic size (Section 2.5.1) of the particles. All particle-sizes of similar aerodynamic properties, regardless of differences in shape, size or density, impact at the same stage.

A camera*** was mounted on the microscope (Figure 16) in order to facilitate sampling analysis and to reduce the tedium of counting the impacted dust particles. Careful focusing was important in order to obtain clear pictures. Colour slide film**** was used. The slides were projected, using a standard slide projector, on a screen containing a grid. The grid consisted of a rectangular pattern of straight lines drawn on large sheets of paper. The use of the grid aided the particle-counting procedure. The particles were counted using a manual counter.

The Andersen sampler impacted particles at 400 sites on each of its six glass-plate stages. A photograph was taken of each of three randomly-chosen deposition sites on each stage. The photographed area was slightly larger than the area of each deposition site as viewed by the microscope. Stage one was viewed under X40 magnification while the other

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* Reichert (X40, X100, X450, X1000), Austria.
** American Optical, 2 mm divisions into units of 0.01 mm.
*** 135 mm, Vitoret, Leitz Wetzlar, Germany.
**** Kodak 2483 photomicrography colour slide film.

Figure 16. Microscope with camera.

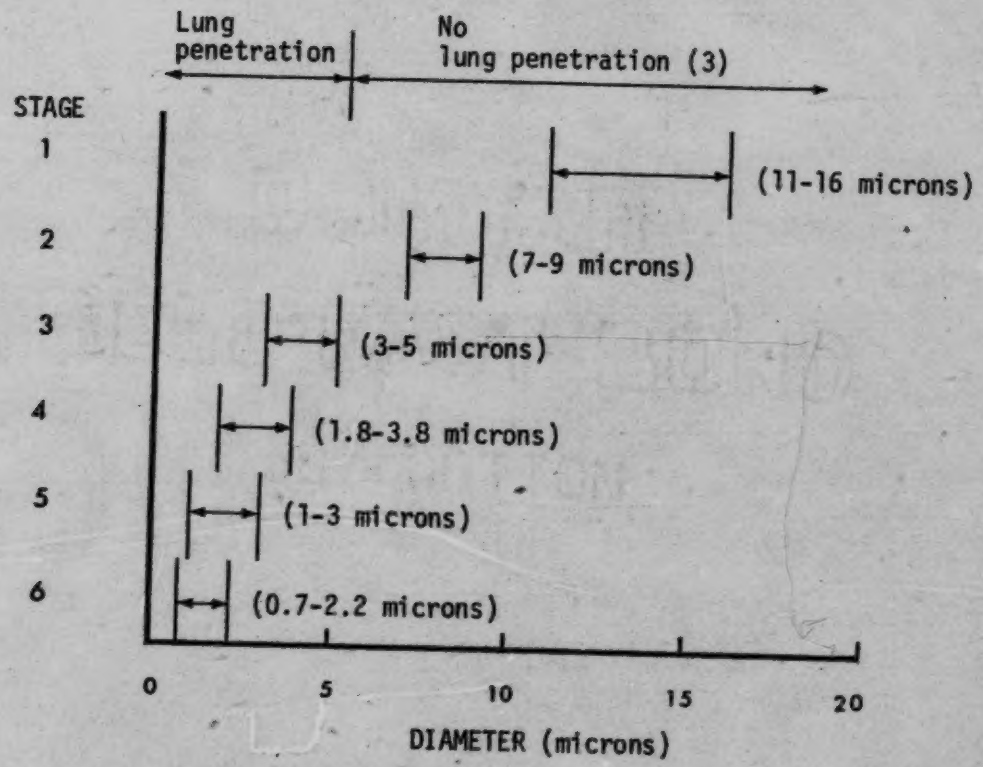

Figure 17. Particle-size ranges as separated by the Andersen air sampler.

five stages were viewed under X100 magnification. Figure 18 presents photomicrographs for a typical sample of atmospheric dust from the experimental pens as impacted on each of the six stages of the sampler.

The sampling time ranged from three to six minutes for a particular treatment so that a countable number of particles would be captured on each of the six sampler stages. Atmospheric dust samples were taken for each treatment for each pen, in the location shown in Figure 19. This location, near the exhaust port, was chosen so that any effects due to anisokinetic sampling would be reduced (7). Photomicrographs were taken immediately after sampling. The pertinent data concerning the atmospheric dust sampling were recorded on a data sheet, a sample of which is presented in Appendix A, Figure A2.

Each treatment was sampled at three different times. Eighteen photomicrographs (three of each of the six sampler stages) were taken of each sample. The average number of particles per cubic foot of air sampled were calculated from the nine slide particle counts representative of each size range for each treatment. These averages for all treatments are presented in Appendix C, Tables C1 to C6. The average number of particles per cubic foot of air sampled for each treatment were calculated for particles less than about five microns in size. This is the maximum size of particle considered able to penetrate lung tissue (3). Therefore, lung particles consist of all particles impacted on stages 3,4,5 and 6 of the sampler. The results are presented in Appendix C, Table C7.

3.4.4 Settled Dust Concentration.

The settled dust determination for each treatment for each pen was made on the basis of the weight of dust which settled on a 3.25 inch diameter plate located on a platform (Figure 19) near the exhaust port.

Stage 1 (11-16 microns X40).

Stage 2 (7-9 microns X100).

Stage 3 (3-5 microns X100).

Stage 4 (1.8-3.8 microns X100).

Stage 5 (1-3 microns X100).

Stage 6 (0.7-2.2 microns X100).

Figure 18. Typical photomicrographs of atmospheric pig-barn dust separated into particle-size ranges.

Figure 19. The dust sampling location inside a pen.

The minimum settled dust sampling period was 24 hours. The settled dust was oven-dried, then weighed.* Appendix A, Figure A3 shows a blank sample data sheet used for determining settled dust concentration. Appendix C, Table C8 presents the settled dust concentration by weight of dust (milligrams) per unit time (hours) per unit area (square centimeters) for each treatment.

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* Mettler H8 automatic balance, Mettler Instrument Corporation, 20 Nassau Street, Princeton, N.J., 08540, U.S.A.

4. DATA ANALYSES AND RESULTS

4.1 Analysis of Variance.

The data in Appendix C, Tables C1 to C8 were subjected to a statistical analysis of variance using a library program (104). A supplementary library program (32) was used to calculate the treatment interaction means. Treatment means are presented in Table 9.

Since the experimental design contained two Latin-squares within a split-plot factorial, the data were analysed by separating the sources of variation into three groups (Table 10).

The analysis of variance results are shown in Table 11 for each of the six atmospheric dust particle-size ranges as separated by the Andersen air sampler, lung penetration particle-size, and settled dust. For each of the three analyses by group of each of the different size ranges, the data were arranged in the appropriate matrix. All the data were used in each analysis. Each source of variation was tested against a suitable error term. The final residual term, (ERROR), is the difference between the sums of squares of all the sources of variation used in the analyses and the total sum of squares.

A Duncan's multiple range test (8) was used to determine exactly which treatment interactions were significantly different from others within the same source of variation containing significant differences as previously indicated by an analysis of variance. Table 12 presents these results. The means and standard deviations included in Table 12 were calculated using a computer program (107).

Due to difficulties with the humidification system, the difference between the two levels of relative humidity (means and standard deviations: H_1; 39.3%, 8.6%, H_2; 45.5%, 7.0%) was not as great

TABLE 9: TREATMENT MEANS FOR PARTICLE-SIZE RANGES.

(Number of particles)

Treatment	One (11-16 microns)	Two (7-9 microns)	Three (3-5 microns)	Four (1.8-3.8 microns)	Five (1-3 microns)	Six (0.7-2.2 microns)	Lung penetration (5 microns)	Settled dust (mg/hr-cm^2) x 10^2
H_1	31,130	20,240	27,620	34,280	36,370	21,640	119,920	5.60
H_2	19,160	13,290	19,820	25,080	25,650	14,680	85,230	4.18
V_1	23,400	14,800	20,460	25,460	25,450	15,050	86,420	5.16
V_2	26,890	18,740	26,990	33,900	36,580	21,270	118,730	4.62
F_1	26,270	16,500	21,380	25,450	25,900	15,640	88,390	6.62
F_2	24,020	17,030	26,070	33,910	36,100	20,680	116,760	3.18
Q_1	24,150	14,500	21,410	27,020	28,260	17,140	93,820	5.03
Q_2	26,140	19,030	26,040	32,340	33,770	19,180	111,330	4.74
Average	25,140	16,760	23,720	29,680	31,010	18,160	102,580	4.89

TABLE 10: SOURCES OF VARIATION GROUPED FOR STATISTICAL ANALYSES.

Group 1	Group 2	Group 3
H	F	V
R/H	Q	Q
V	FQ	H
P/V	HF	VQ
VR/H	HQ	VQH
HP/V	HFQ	Error 3
R/HP/V	Error 2	TOTAL
Error 1	TOTAL	
TOTAL		

Nomenclature

H...Humidity

R...Rows

V...Volume

P...Pens

F...Feed

Q...Air-Flow Rate

/...Within

Error (1,2 or 3)...Residuals for Group 1,2 or 3

TABLE 11: ANALYSIS OF VARIANCE FOR PARTICLE-SIZE RANGES.

		ONE (11-16 MICRONS)		TWO (7-9 MICRONS)		THREE (3-5 MICRONS)		FOUR (1.8-3.8 MICRONS).	
Sources of Variation	Degrees of Freedom	Mean Squares	F-Values	Mean Squares	F-Values	Mean Squares	F-Values	Mean Squares	F-Values
H (Humidity)	1	1,146,800,000	2.88	387,160,000	2.01	486,800,000	3.44	677,150,000	2.46
ERROR (1) (Rows/H)	6	398,900,000		192,680,000		141,500,000		272,630,000	
V (Volume)	1	97,266,000	1.77	124,320,000	1.68	340,670,000	2.28	569,700,000	3.22
ERROR (2) (Pens/V)	2	55,054,000		74,380,000		149,900,000		177,100,000	
H x V	1	103,212,000	2.29	2,283,000	<1.00	393,800	<1.00	3,139,000	<1.00
ERROR (3) (H x P/V)	2	44,951,000		78,625,000		54,670,000		101,230,000	
F (Feed)	1	40,612,000	<1.00	2,180,000	<1.00	175,830,000	5.34*	572,090,000	5.12*
Q (Air Flow Rate)	1	31,661,000	<1.00	163,840,000	14.05**	171,450,000	5.17*	226,510,000	2.01
F x Q	1	25,686,000	<1.00	39,589,000	3.40	50,727,000	1.54	113,240,000	1.01
H x F	1	18,742,000	<1.00	25,584,000	2.20	172,380,000	5.21*	523,450,000	4.70
H x Q	1	228,180,000	4.65	180,820,000	15.50**	146,080,000	4.44	157,430,000	1.41
V x Q	1	3,206,800	<1.00	1,326,000	<1.00	1,055,000	<1.00	26,059,000	<1.00
H x F x Q	1	553,900	<1.00	23,142,000	1.98	66,560,000	2.02	274,230,000	2.46
H x V x Q	1	17,776,000	<1.00	11,440,000	<1.00	25,540,000	<1.00	34,356,000	<1.00
ERROR (4) (Residual)	10	48,788,000		11,642,000		32,993,000		111,690,000	
TOTAL	31								

* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE 11: ANALYSIS OF VARIANCE FOR PARTICLE-SIZE RANGES (continued).

		FIVE (1-3 MICRONS)		SIX (0.7-2.2 MICRONS)		LUNG PENETRATION (<5 MICRONS)		SETTLED DUST	
Sources of Variation	Degrees of Freedom	Mean Squares	F-Values	Mean Squares	F-Values	Mean Squares	F-Values	Mean Squares	F-Values
H (Humidity)	1	920,200,000	3.39	387,320,000	4.63	9,624,000,000	3.70	15.834	7.90*
ERROR (1) (Rows/H)	6	271,070,000		83,653,000		2,554,000,000		1.996	
V (Volume)	1	991,240,000	7.75	309,200,000	13.00	8,353,000,000	4.80	2.274	<1.00
ERROR (2) (Pens/V)	2	127,540,000		23,774,000		1,727,000,000		9.154	
H x V	1	5,780,000	<1.00	4,720,000	<1.00	48,670,000	<1.00	9.713	388.00**
ERROR (3) (H x P/V)	2	89,650,000		4,766,000		844,500,000		0.025	
F (Feed)	1	828,240,000	8.05*	203,970,000	3.57	6,438,000,000	7.36*	93.81	54.5**
Q (Air Flow Rate)	1	242,880,000	2.35	33,436,000	<1.00	2,451,000,000	2.80	0.676	<1.00
F x Q	1	24,465,000	<1.00	63,900	<1.00	527,300,000	<1.00	0.079	<1.00
H x F	1	349,400,000	3.39	121,880,000	2.14	4,322,000,000	4.94	2.252	1.31
H x Q	1	88,113,000	<1.00	14,111,000	<1.00	1,427,000,000	1.63	0.107	<1.00
V x Q	1	93,845,000	<1.00	19,453,000	<1.00	409,200,000	<1.00	0.079	<1.00
H x F x Q	1	103,970,000	1.01	19,298,000	<1.00	1,545,000,000	1.77	0.351	<1.00
H x V x Q	1	27,714,000	<1.00	5,064,000	<1.00	339,700,000	<1.00	0.134	<1.00
ERROR (4) (Residual)	10	102,960,000		56,921,000		874,330,000		1.724	
TOTAL	31								

* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE 12: SIGNIFICANT TREATMENTS, BY ANALYSIS OF VARIANCE.

Particle size	Source of variation	Treatments and directions of significance with means and standard deviations	Level of significance
Stage two	Q	$Q_2(19{,}030 \pm 11{,}500) > Q_1(14{,}500 \pm 5{,}130)$	**
	HQ	$H_1Q_2(24{,}880 \pm 13{,}190) > H_1Q_1, H_2Q_1, H_2Q_2(14{,}060 \pm 5{,}190)$	**
Stage three	F	$F_2(26{,}070 \pm 12{,}130) > F_1(21{,}380 \pm 7{,}490)$	*
	Q	$Q_2(26{,}040 \pm 12{,}290) > Q_1(21{,}410 \pm 7{,}250)$	*
	HF	$H_1F_2(32{,}290 \pm 13{,}340) > H_1F_1, H_2F_2, H_2F_1(20{,}870 \pm 7{,}210)$	*
Stage four	F	$F_2(33{,}910 \pm 17{,}910) > F_1(25{,}450 \pm 8{,}570)$	*
Stage five	F	$F_2(36{,}100 \pm 18{,}030) > F_1(25{,}900 \pm 8{,}410)$	*
Lung penetration	F	$F_2(116{,}760 \pm 56{,}105) > F_1(88{,}390 \pm 27{,}130)$	*
Settled dust	H	$H_1(5.60 \pm 2.67) > H_2(4.18 \pm 1.82)$	*
	HV	$H_1V_1(6.41 \pm 3.13) > H_1V_2(4.78 \pm 1.99) > H_2V_2(4.47 \pm 2.09) > H_2V_1(3.9 \pm 1.61)$	**
	F	$F_1(6.62 \pm 2.01) > F_2(3.18 \pm 1.1)$	

* Significant at the 5% probability level.
** Significant at the 1% probability level.

as desired. Therefore, the relative humidities (Appendix C, Table C11) were tested (45) to determine that they were in fact significantly different at the five percent level of significance.

4.2 Analysis of Covariance.

Supplementary to the analysis of variance, an analysis of covariance was conducted on the dust data (Appendix C, Tables C1 to C8) using the covariates (Appendix C, Tables C9 and C10) pig weight, and pen temperature during sampling. The sources of variation were grouped in the same three groups as used previously in the analysis of variance (Table 9). This analysis of covariance was performed in two steps. Firstly, the covariate cross-products were obtained using a Fortran computer program (31). Secondly, the covariate cross-products were used in APL computer programs, Appendix D, Tables D1 to D3, developed by the author, to calculate the adjusted sums of squares and test the resulting mean sums of squares for significance. The covariates, weight and temperature, were analysed both separately and combined. Appendix E, Tables E1 to E22, presents the analyses of covariance for each of the six atmospheric dust particle-size ranges, lung penetration particles, and settled dust.

The analysis of covariance reduced the effective degrees of freedom of the various error terms by one for each covariate used. In some cases, the lack of sufficient degrees of freedom prevented the meaningful testing of a source of variation for significance.

The settled dust was not analysed using temperature as a covariate because the recorded temperatures were those coinciding with atmospheric dust sampling only.

The adjusted means for the treatments and treatment interactions could not be obtained. Therefore, only the relative changes in the significance of sources of variation were determined. Tables 13 to 15 present a subjective analysis based on the size of the covariance F values and indicate either an increase or a decrease in significance.

TABLE 13: CHANGES IN SIGNIFICANCE WITH THE USE OF THE COVARIATE, TEMPERATURE..

Particle-size range	Source of variation	Change in significance	Significance by analysis of variance	Significance by analysis of covariance
Stage one	HV	increase	ns	*
Stage two	HV	increase	ns	**
	Q	increase	**	**
	HQ	increase	**	**
Stage three	H	increase	ns	*
	HV	increase	ns	*
	Q	increase	*	*
	F	decrease	*	ns
	HF	decrease	*	ns
Stage four	V	increase	ns	*
	HV	increase	ns	**
	F	decrease	*	ns
Stage five	V	increase	ns	*
	HV	increase	ns	**
	F	decrease	*	ns
Stage six	H	increase	ns	*
	V	increase	ns	*
	HV	increase	ns	**
	Q	increase	ns	**
Lung penetration	V	increase	ns	*
	HV	increase	ns	**
	Q	increase	ns	*
	F	decrease	*	ns

ns	Not significant.
*	Significant at the 5% probability level.
**	Significant at the 1% probability level.

TABLE 14: CHANGES IN SIGNIFICANCE WITH THE USE OF THE COVARIATE, PIG WEIGHT.

Particle-size range	Source of variation	Change significance	Significance by analysis of variance	Significance by analysis of covariance
Stage one	H	increase	ns	*
	HV	increase	ns	*
Stage two	V	increase	ns	*
	HV	increase	ns	**
	Q	increase	**	**
	HQ	increase	**	**
Stage three	HV	increase	ns	**
	F	decrease	*	ns
	Q	decrease	*	ns
	HF	decrease	*	ns
Stage four	HV	increase	ns	**
	F	decrease	*	ns
Stage five	V	increase	ns	*
	HV	increase	ns	**
	F	decrease	*	ns
Stage six	H	increase	ns	*
	V	increase	ns	*
Lung penetration	HV	increase	ns	**
	F	decrease	*	ns
Settled dust	H	decrease	*	*
	HV	increase	**	**
	F	decrease	**	**

ns Not significant
* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE 15: CHANGES IN SIGNIFICANCE WITH THE USE OF THE COVARIATES, TEMPERATURE AND PIG WEIGHT.

Particle-size range	Source of variation	Change significance	Significance by analysis of variance	Significance by analysis of covariance
Stage one	H	increase	ns	*
Stage two	Q	decrease	**	**
	HQ	decrease	**	**
Stage three	H	increase	ns	*
	Q	increase	*	*
	F	decrease	*	ns
	HF	decrease	*	ns
Stage four	F	decrease	*	ns
Stage five	F	decrease	*	ns
Stage six	H	increase	ns	*
	Q	increase	ns	**
Lung penetration	F	decrease	*	ns

ns Not significant.
* Significant at the 5% probability level.
** Significant at the 1% probability level.

5. DISCUSSION

5.1 The Experimental Procedure.

The purpose of this experiment was to determine if the variables pen volume, relative humidity, feeding method and air-flow rate were associated with atmospheric dust concentrations in a fairly typical pig environment. The effects of dust on pig performance or health were not a part of this study.

Dust was sampled from four independent pens each containing ten pigs. The pigs adapted well to the pens and appeared to be under no stress resulting from either the experimental treatments or the management system.

Included in this study were the supplementary factors of pig weight, pen temperature during sampling, and settled dust concentrations. An advantage could have been gained in maintaining a constant pen temperature if the experiment had been conducted during cooler weather.

Atmospheric dust concentrations were determined by counting photomicrographs (slides) of particles collected in six size ranges with a cascade impactor. The photomicrographic method was quite successful, although tedious. From a close observation of the dust samples and slides, atmospheric dust particles were thought to originate primarily from feed. About one percent of the particles of size range one were pieces of hair. Also in size range one, about ten percent of the particles appeared to have originated from skin. About five percent of the particles of size range two appeared to have originated from skin. Shape and colour were the basis for these observations. Dark fibrous particles were assumed to be hair, while thin, flat, translucent or white particles were assumed to be skin. The remaining cubical or spherical particles were assumed to have originated from feed. The use of the cascade impactor to collect gravimetric samples of dust was unsuccessful.

The assumption was made that the treatments by themselves (no pigs present) could create no differences in dust concentrations. Only the pigs caused dust; the treatments just modified the amount of dust.

5.2 The Analysis of Variance Results.

The analysis of variance procedure was discussed previously in Section 4.1. The significant results were presented in Table 18. There were no significant differences among treatments for particle-size ranges one and six. These size ranges represented the extremes of atmospheric particle-size and, therefore, contained particles either so large or so small as to be unaffected by the treatments investigated.

The low air-flow rate was associated with a significantly greater number of dust particles in size ranges two and three than was the high air-flow rate. The aerodynamic characteristics of these size ranges of particles in all probability could be such that they contain the only particles affected to any great extent by the air velocities and turbulence prevailing within the pens.

Air-flow rates can be stated in terms of either ventilating-volume in units of cubic feet of air per minute, cfm, or frequency of ventilation in units of room air-changes per hour, AC/hr (46). The cubic feet per minute designation was used throughout the experiment. Table 22 shows the conversion of air-flow rate from cubic feet per minute to air changes per hour. Since pen volume is used in the conversion, the source of variation, air-flow rate with pen volume, QV, also represents air-flow rate. No significant differences in dust concentrations resulted from the air-flow rate with volume interaction. This, coupled with the fact that

TABLE 16: AIR-FLOW RATE UNIT CONVERSION.

Treatment Nomenclature	Air-flow rate (cfm)	Conversion	Air-flow rate (air changes/hr)
Q_1V_1	350	$350 \frac{ft^3}{min} \times 60 \frac{min}{hr} \times 780 \frac{ft^3}{air\ change}$	= 27.0
Q_1V_2	350	$\frac{350 \times 60}{390}$	= 54.0
Q_2V_1	175	$\frac{175 \times 60}{780}$	= 13.5
Q_2V_2	175	$\frac{175 \times 60}{390}$	= 27.0

air-flow rates were significant (in particle-size ranges two and three), indicated that the two pen volumes could be opposing each other regarding their effect on atmospheric dust concentrations. This differs from Gordon's conclusions (46) that dust and odour are intimately linked and that frequency of ventilation (air-changes per hour) was a more important consideration in controlling odour intensity than was ventilating volume (cubic feet of air per hour).

Significant differences due to feeding methods were found for the small particle-size ranges three, four, five and lung penetration size. For these size ranges, the self-feeding resulted in greater atmospheric dust concentration than did floor-feeding. In fact, floor-feeding yielded about two-thirds as many dust particles as did self-feeding. The pigs whether floor-fed or self-fed consumed approximately the same amounts of feed. However, the self-fed pigs appeared to spend a much longer time eating than did the floor-fed pigs. The longer eating time of the self-fed pigs plus the fact that the self-fed pigs played with the excess feed probably contributed to the significantly different effects attributed to the feeding methods.

The lack of significant differences due to relative humidity was unexpected based on some of the literature reviewed (4,9,46,47,48,96). This can probably be explained by the small, although statistically significant, difference (about six percentage points) between the low and high relative humidities. This small difference in relative humidity is suspected to have resulted from an inadequacy or malfunction of the steam humidifier used to condition the ventilation air.

The interaction of low humidity and low air-flow rate was associated with a significantly greater concentration of atmospheric dust only in particle-size range two. The interaction of low relative humidity with the self-feeding method was associated with significantly larger atmospheric dust concentration only in particle-size range three. The preceding interactions can possibly be explained by the adsorption and subsequent absorption of water vapour (Section 2.5.7) by dust particles in the more humid environment. These heavier particles would tend to settle quickly and not be free to circulate as atmospheric dust. This could be the same reason that the low relative humidity resulted in a significantly greater amount of settled dust than was the high relative humidity.

The floor-feeding treatment was associated with a significantly greater amount of settled dust than was the self-feeding treatment. This could be due to the intense activity of the pigs during floor-feeding when a great deal of visible dust was observed for a short period of time. The self-fed pigs even while eating were not nearly as active as those being floor-fed.

All the settled-dust treatment interactions of humidity with volume were highly significantly different from each other. The effect of low humidity with large volume was greater than that of low humidity with small volume which, in turn, was greater than that of high humidity with small volume. This in turn was greater than that of high humidity with large volume. The fact that the low humidity interactions were associated with greater settled dust concentrations than were the high humidity treatment interactions might be explained with reasoning similar to that used previously when discussing significant differences due to relative humidities. The volume effect could be connected in part with pen surface area or the distance a particle might have to travel before contacting an obstruction upon which it could settle.

5.3 The Analysis of Covariance Results.

The analysis of covariance procedure (Section 4.2) used to obtain the data presented in Appendix E was neither complete nor efficient in terms of time-and-labour-input versus information-output. Adjusted treatment means were not available and, therefore, significant sources of variation could not be tested with a multiple range test to determine which of the treatments within a source of variation were significant. Also, the direction of significance could not be obtained. However, the analysis of covariance was conducted to reveal if the covariates, pen temperature during sampling and pig weight, either increased or decreased the levels of significance previously determined with analysis of variance.

The pen temperature was supposed to remain constant according to the desired experimental design. However, due to outdoor temperature influences together with a total lack of cooling ability, the average pen temperatures, in degrees Fahrenheit, during atmospheric dust sampling ranged from 66.6 to 85.4 with a mean and standard deviation of 76.8 and 5.3, respectively. The average pig weights, in pounds, during the treatments ranged from 65.5 to 128.8 with a mean and standard deviation of 99.4 and 20.0, respectively. The experimental design with the two Latin squares incorporated into the split-plot factorial ensured that the effects of any factors related to time (particularly temperature and pig weights) were evenly distributed over all the treatments. Thus, temperature and pig weight could not have unduly biased treatment results.

A study of the analysis of covariance data, Appendix E, and the comparison, Tables 13,14 and 15, of the analysis of covariance results with those of the analysis of variance indicate that both temperature and weight were associated with dust concentrations. Temperature effects produced a greater increase in significance than either weight or the combination of temperature and weight. The use of the covariates separately generally increased the significance of sources of variation while used together the covariates generally reduced the significance compared to the results of the analysis of variance.

The separate use of the two covariates increased the significance associated with humidity and humidity with volume interactions. The significant differences of feeding methods were removed entirely. The removal of significance associated with feeding methods by the covariate weight could be explained in part by the relationship between the amount of feed fed and pig weight (Table 6). The removal of significance associated with feeding methods by temperature probably could be due to a response of the activity of the pigs to temperature. Pigs generally become less active with increasing temperature (11) and a diminished activity is assumed to yield less dust (10). The amount of feed fed per animal seemed to be connected with a greater effect on dust concentration than does the actual method of feeding; that is, the more feed, the more dust.

The combined use of the covariates increased the significance of humidity associated with dust concentrations. This emphasizes the importance of both temperature and pig weight as factors influencing atmospheric dust concentrations.

6. CONCLUSIONS

Subject to the conditions of this experiment the following conclusions were reached.

1. The different size ranges of atmospheric dust were not similarly affected by the same treatments.
2. A relative humidity difference of less than six percentage points did not affect atmospheric dust concentrations, but was associated with a statistically significant effect on settled dust concentrations. The lower relative humidity resulted in the greater amount of settled dust.
3. Self-feeding was associated with a significantly greater amount of atmospheric dust than was floor-feeding, but the latter was associated with a highly significantly greater amount of settled dust than was self-feeding.
4. Air-flow rates, when expressed in units of air-changes-per-hour, resulted in no significant differences in dust concentrations. However, a low air-flow rate (175 cfm) was associated with a significantly greater number of atmospheric dust particles in the particle-size ranges, 7 to 9 microns and 3 to 50 microns, than was a high air-flow rate (350 cfm).
5. Pen volumes and the interaction of relative humidity with pen volumes resulted in significant differences between dust concentrations only after the separate effects of temperature and pig weight were removed.
6. Both atmospheric and settled dust were composed primarily of feed particles.
7. The more important factors associated with dust concentrations,

in descending order, were considered from observation to be; activity of the pigs, temperature, humidity with volume interactions, relative humidity, amount of feed fed, feeding method, pig weight, and air-flow rate.

7. SUGGESTIONS FOR FURTHER STUDY

As a result of this experiment, additional areas of concern have been located and are discussed in this section.

1. A sensitivity analysis of the factors significantly affecting dust concentrations should be conducted to aid in ascertaining a cause-effect relationship. This could be carried out in an experiment similar to this one by subjecting pigs to different increments of variables and statistically comparing the resulting dust concentrations.
2. The facts concerning probable disease-dust symbiosisms should be established to determine if some diseases are caused by dust or if dust just facilitates the transport and emergence of disease. Some histopathological studies (34,74) have been conducted already. Further studies of the respiratory systems of individual pigs each subjected to different controlled increments of dust concentrations and/or airborne disease could yield this type of information.
3. The results of some studies (34,74) would indicate that, although respiratory damage due to dust was discovered, no economic losses would normally result from that kind of damage. Market pigs are subjected to dust during a lifetime of five months. This short exposure time period could be unimportant in that little damage is caused or that the damage that is caused is primarily to the respiratory system which is considered non-edible and of little economic consequence. However, financial losses could be incurred if the performance of the pigs in terms of feed conversion, rate of gain and

carcass quality was negatively influenced by dust.

4. Since non-organic dust is known to cause respiratory problems (Section 2.8) and since there are no good effects attributed to organic dust, then acceptable or tolerance levels of dust concentrations should be established for pigs, pig barns and pig farmers.

5. Since pig activity is considered to be an important variable associated with atmospheric dust concentration (10,46), a method of monitoring and quantifying the activity of pigs should be developed. The activity of pigs then could be related to such factors as pen temperatures, relative humidity, air-flow rate and pig weight in order to eliminate the present unknown effects of pig activity and to allow a more complete study of the factors causing dust.

6. Additional dust concentration research should employ a continuous automatic monitoring system. This should ensure a more complete study with a possible reduction in labour although with a greater financial investment.

7. The possible stratification of atmospheric dust particles and the variation of dust concentrations according to location should be investigated. Dust samples could be obtained at various sites within the pigs' environment in order that dust studies could eventually be related to the dust concentration in the vicinity of the air respired by pigs.

8. Additional computer programs for analysis of covariance should be developed. These programs should be easily adaptable to different experimental designs. For completeness, the

significance of treatments should be tested by a multiple range test rather than just testing the sources of variation for significance. Also, the adjusted treatment means and standard deviations should be available as output.

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APPENDIX A. SAMPLE DATA SHEETS.

Included in this appendix are samples of the data sheets used to record the raw information for the experiment.

PEN # ____

TREATMENT ____

TREATMENT PERIOD ____ to ____

TREATMENT DESCRIPTIONS

V 1 / 2 = 780 / 390 cubic feet pen volume

H 1 / 2 = natural / artificial relative humidity

F 1 / 2 = floor-fed / self-fed

Q 1 / 2 = 350 / 175 cfm air flow rate

WEIGHT RECORD

DATE ____

FEED CONSUMPTION

PIG #	WEIGHT (lbs)	DATE	WEIGHT OF FEED ADDED (lbs)

TOTAL ____

AVERAGE ____

Figure A1. Blank sample data sheet for recording pig data.

ATMOSPHERIC DUST CONCENTRATIONS

Pen # ____ Treatment V 1 / 2 H 1 / 2 F 1 / 2 Q 1 / 2 Date ____________
Temperatures: Uncorrected dry bulb ___ F Corrected dry bulb ___ F Relative Humidity ___%
Uncorrected wet bulb ___ F Corrected wet bulb ___ F
Time of sample ______ Duration of sample ______ seconds
Film # _______ Film Time ______________

Slide #	Sampler stage #	Microscope power	Film exposure time (seconds)	# of particles per slide	Average # of particles per slide for each stage	# of particles per stage	# of particles per cubic foot of air

Figure A2. Blank sample data sheet for recording atmospheric dust concentration data.

SETTLED DUST DETERMINATIONS

	PEN # 1	PEN # 2	PEN #3	PEN # 4
Treatment				
Plate #				
Settled dust + plate (gms)				
Plate (gms)				
Settled dust (gms)				
Settling period (hours)				
Average settling rate of dust (gms/hour)				

Figure A3. Blank sample data sheet for recording settled dust determinations.

APPENDIX B. THERMOCOUPLE CALIBRATION.

Since the thermocouple recorder range (-20 to 120 degrees Fahrenheit) did not include both the ice-point of water (32.0 degrees Fahrenheit) and the boiling-point temperature of water (212.0 degrees Fahrenheit), a glass thermometer with a range of -30 to 220 degrees Fahrenheit and a sling psychrometer with a range of zero to 120 degrees Fahrenheit were used to calibrate the eight thermocouples. The calibration of the wet-bulb thermocouples was especially important since they were not located in an airstream such that true readings could be obtained directly. The air-movement in the pens was considerably less than the range of 800 to 900 feet per minute that is required to obtain an accuracy of about 0.5 percent when using a set-bulb thermometer (59).

Simultaneous temperature readings were recorded (Table B1) for each of the temperature indicating devices for each of three different occasions. This table also indicates the thermocouple number, function and location. Readings were allowed to stabilize before being recorded. The ice-point readings were obtained by immersing the thermometer bulbs and thermocouple junctions in a constantly-stirred mixture of ice and distilled water. The average of three readings using three different mixtures of ice and water determined the ice-point temperature reading for each of the temperature indicating devices. Readings of the boiling-point temperature of water for the thermometer were obtained by immersing the thermometer bulb in constantly-stirred boiling distilled water. The average of three readings using three different containers of boiling water was used as the boiling-point temperature reading. The actual boiling-point temperature was calculated taking into account coincident barometric pressure (29.59 inches of mercury, sea level) for Edmonton International Airport. The actual barometric pressure adjusted to Edmonton's elevation (2360 feet above sea level) was 691.6 mm of mercury (112). The boiling-point of water at this pressure is 97.4 degrees centigrade (207.3 degrees Fahrenheit). This theoretical boiling-point was assumed, for all the intentions and purposes of the experiment, to be equal to the boiling-point reading of the glass thermometer (208.0 degrees Fahrenheit). In addition, the theoretical ice-point temperature and the thermometer ice-point reading were identical (32.0 degrees Fahrenheit). Therefore, the actual temperature, T_a, was assumed to be equal to the temperature reading, T_r, of the glass thermometer, g.

$$T_a = T_{rg} \tag{B1}$$

The temperature readings recorded in Table B1 are corrected to actual temperatures and compared in order to obtain calibration equations for each of the eight thermocouples. The dry-bulb sling psychrometer (d) readings were compared to those of the glass thermometer. The average difference between the accurate glass thermometer readings and the dry-bulb sling psychrometer readings was -1.1 Fahrenheit degrees. Therefore,

$$T_a = T_{rd} - 1.1 \tag{B2}$$

Table B2 is a comparison of the dry-bulb sling psychrometer readings (obtained from Table B1, then corrected to actual temperatures using equation (B2) to the wet-bulb sling psychrometer (w) readings. The wet sock had been removed from the wet-bulb sling psychrometer.

Therefore,

$$T_a = T_{rw} - 0.5 \tag{B3}$$

TABLE B1: DATA FOR THE CALIBRATION OF THERMOCOUPLES.

	Temperatures (degrees F.)							
Thermocouple number	1	2	3	4	5	6	7	8
function, wet-bulb (w) dry-bulb (d)	w	d	w	d	w	d	w	d
Location	pen #1		pen# 2		pen# 3		pen# 4	
Thermocouple readings (-20 to 120)	48.5	63.5	51.5	64.5	51.0	65.0	49.5	63.7
	49.0	64.0	51.5	64.5	51.0	65.0	50.5	63.8
Corresponding sling psychrometer readings (0 to 120)	44.5	67.0	45.0	67.0	46.0	67.5	46.0	67.0
	45.5	66.0	45.5	67.0	46.0	68.0	36.0	66.5
	45.0	67.0	45.0	67.5	45.5	68.5	44.5	67.0
Corresponding glass thermometer readings (-30 to 220)		66.0		66.0		66.0		65.0
		65.5		66.0		67.0		65.0
		65.8		66.0		67.0		66.0
Thermocouple ice-points	29.5	29.5	29.5	29.5	29.8	30.0	30.0	30.0
	29.5	29.5	29.5	29.5	29.8	30.0	30.0	30.0

Corresponding sling psychrometer readings (wet-bulb with the sock removed)

wet-bulb	72.8	72.0	70.0	59.0	32.5
dry-bulb	73.0	73.0	70.5	59.8	33.0

Thermometer ice-point reading = 32.0
Thermometer boiling-point reading = 208.0
Sling psychrometer wet-bulb ice poing reading = 32.5
Sling psychrometer dry-bulb ice point reading = 33.0
Barometric pressure (sea level) = 29.59 inches of mercury

TABLE B2: TEMPERATURE COMPARISON (WET-BULB SLING PSYCHROMETER).

	Temperatures (degrees F.)			
T_a	71.9	71.9	69.4	58.7
T_{rw}	72.8	72.0	70.0	59.0
Difference	-0.9	-0.1	-0.6	-0.3
Average difference = -0.5				

In the same manner, the wet bulb sling psychrometer readings were compared in Table B3 to the individual set-bulb thermocouples. The wet-bulb sling psychrometer readings were obtained from Table B1, then corrected to actual temperatures using equation (B3). Therefore, the calibration equations for the wet-bulb thermocouples are:

$$T_a = T_{r(tc1)} - 4.5 \tag{B4}$$

$$T_a = T_{r(tc3)} - 7.0 \tag{B5}$$

$$T_a = T_{r(tc5)} - 5.7 \tag{B6}$$

$$T_a = T_{r(tc7)} - 5.0 \tag{B7}$$

Similarly, the actual temperatures of the glass thermometer are compared, in Table B4, to the dry-bulb thermocouple readings. Therefore, the calibration equations for the dry-bulb thermocouples are:

$$T_a = T_{r(tc2)} + 1.8 \tag{B8}$$

$$T_a = T_{r(tc4)} + 1.4 \tag{B9}$$

$$T_a = T_{r(tc6)} + 1.5 \tag{B10}$$

$$T_a = T_{r(tc8)} + 1.5 \tag{B11}$$

TABLE B3: TEMPERATURE COMPARISON (WET-BULB THERMOCOUPLES).

	Temperatures (degrees F.)		
	Thermocouple # 1 (tc1)		
T_a	44.0	45.0	44.5
$T_{r(tc1)}$	48.5	49.0	49.5
Difference	-4.5		
Average difference = -4.5			
	Thermocouple # 3 (tc3)		
T_a	44.5	45.0	44.5
$T_{r(tc3)}$	51.5	51.5	51.5
Difference	-7.0	-6.5	-7.5
Average difference = -7.0			
	Thermocouple # 5 (tc5)		
T_a	45.5	45.5	45.0
$T_{r(tc5)}$	51.0	51.0	51.0
Difference	-5.5	-5.5	-6.0
Average difference = -5.7			
	Thermocouple # 7 (tc7)		
T_a	45.5	45.5	44.0
$T_{r(tc7)}$	49.5	50.5	50.0
Difference	-4.0	-5.0	-6.0
Average difference = -5.0			

TABLE B4: TEMPERATURE COMPARISON (DRY-BULB THERMOCOUPLES).

	Temperatures (degrees F.)		
	Thermocouple # 2 (tc2)		
T_a	66.0	65.5	65.8
$T_{r(tc2)}$	63.5	64.0	64.5
Difference	2.5	1.5	1.3
Average difference = 1.8			
	Thermocouple # 4 (tc4)		
T_a	66.0	66.0	66.0
T_r(tc4)	64.5	64.5	64.8
Difference	1.5	1.5	1.2
Average difference = 1.4			
	Thermocouple #6 (tc6)		
T_a	66.0	67.0	67.0
$T_{r(tc6)}$	65.0	65.0	65.5
Difference	1.0	2.0	1.5
Average difference = 1.5			
	Thermocouple # 8 (tc8)		
T_a	65.0	65.0	66.0
$T_{r(tc8)}$	63.7	63.8	64.0
Difference	1.3	1.2	2.0
Average difference = 1.5			

APPENDIX C. EXPERIMENTAL DATA.

These are the data averaged from the raw data and used in the statistical analyses (Section 4).

TABLE C1: ATMOSPHERIC DUST CONCENTRATIONS FOR STAGE ONE SIZE RANGE (11 - 16 MICRONS).

(Number of particles)

		V_1		V_2	
		pen 1	pen 2	pen 3	pen 4
H_1	T_1	F_2Q_2 53,840	F_2Q_1 46,180	F_1Q_2 43,750	F_1Q_1 39,820
	T_3	F_1Q_2 49,090	F_1Q_1 24,940	F_2Q_2 37,630	F_2Q_1 25,260
	T_6	F_1Q_1 26,200	F_2Q_2 16,890	F_2Q_1 18,400	F_1Q_2 25,820
	T_7	F_2Q_1 14,460	F_1Q_2 17,850	F_1Q_1 24,450	F_2Q_2 33,480
H_2	T_2	F_2Q_1 28,740	F_1Q_2 28,540	F_1Q_1 36,310	F_2Q_2 27,540
	T_4	F_1Q_2 8,200	F_1Q_1 8,440	F_2Q_2 14,600	F_2Q_1 14,110
	T_5	F_1Q_1 19,360	F_2Q_2 16,060	F_2Q_1 21,470	F_1Q_2 25,850
	T_8	F_2Q_2 7,210	F_2Q_1 8,380	F_1Q_2 11,840	F_1Q_1 29,840

TABLE C2: ATMOSPHERIC DUST CONCENTRATIONS FOR STAGE TWO SIZE RANGE (7 - 9 MICRONS).

(Number of particles)

		V_1		V_2	
		pen 1	pen 2	pen 3	pen 4
H_1	T_1	F_2Q_2 42,900	F_2Q_1 20,270	F_1Q_2 37,850	F_1Q_1 24,960
	T_3	F_1Q_2 27,630	F_1Q_1 12,420	F_2Q_2 33,580	F_2Q_1 18,760
	T_6	F_1Q_1 16,490	F_2Q_2 9,400	F_2Q_1 10,530	F_1Q_2 12,000
	T_7	F_2Q_1 9,630	F_1Q_2 9,587	F_1Q_1 11,780	F_2Q_2 26,130
H_2	T_2	F_2Q_1 16,830	F_1Q_2 16,570	F_1Q_1 19,990	F_2Q_2 19,780
	T_4	F_1Q_2 9,220	F_1Q_1 7,010	F_2Q_2 11,900	F_2Q_1 10,880
	T_5	F_1Q_1 12,150	F_2Q_2 11,730	F_2Q_1 15,230	F_1Q_2 21,640
	T_8	F_2Q_2 7,800	F_2Q_1 7,090	F_1Q_2 6,750	F_1Q_1 18,040

TABLE C3: ATMOSPHERIC DUST CONCENTRATIONS FOR STAGE THREE SIZE RANGE (3 - 5 MICRONS).

(Number of particles)

		V_1		V_2	
		pen 1	pen 2	pen 3	pen 4
H_1	T_1	F_2Q_2 43,300	F_2Q_1 25,410	F_1Q_2 30,960	F_1Q_1 29,740
	T_3	F_1Q_2 33,750	F_1Q_1 14,290	F_2Q_2 53,220	F_2Q_1 33,070
	T_6	F_1Q_1 21,480	F_2Q_2 16,900	F_2Q_1 19,750	F_1Q_2 17,570
	T_7	F_2Q_1 22,320	F_1Q_2 16,560	F_1Q_1 19,330	F_2Q_2 44,350
H_2	T_2	F_2Q_1 29,970	F_1Q_2 19,980	F_1Q_1 25,800	F_2Q_2 29,810
	T_4	F_1Q_2 17,290	F_1Q_1 19,030	F_2Q_2 16,580	F_2Q_1 17,200
	T_5	F_1Q_1 13,340	F_2Q_2 19,330	F_2Q_1 21,450	F_1Q_2 29,160
	T_8	F_2Q_2 13,650	F_2Q_1 10,790	F_1Q_2 14,220	F_1Q_1 29,590

TABLE C4: ATMOSPHERIC DUST CONCENTRATIONS FOR STAGE FOUR SIZE RANGE (1.8 - 3.8 MICRONS).

(Number of particles)

		V_1		V_2	
		pen 1	pen 2	pen 3	pen 4
H_1	T_1	F_2Q_2 41,590	F_2Q_1 26,630	F_1Q_2 14,780	F_1Q_1 30,090
	T_3	F_1Q_2 39,790	F_1Q_1 17,660	F_2Q_2 85,030	F_2Q_1 44,173
	T_6	F_1Q_1 28,340	F_2Q_2 23,560	F_2Q_1 26,060	F_1Q_2 23,930
	T_7	F_2Q_1 36,600	F_1Q_2 25,810	F_1Q_1 27,660	F_2Q_2 58,780
H_2	T_2	F_2Q_1 38,520	F_1Q_2 24,200	F_1Q_1 33,780	F_2Q_2 37,930
	T_4	F_1Q_2 20,370	F_1Q_1 15,110	F_2Q_2 18,280	F_2Q_1 23,560
	T_5	F_1Q_1 13,360	F_2Q_2 25,600	F_2Q_1 25,990	F_1Q_2 41,630
	T_8	F_2Q_2 16,830	F_2Q_1 15,400	F_1Q_2 19,340	F_1Q_1 31,380

TABLE C5: ATMOSPHERIC DUST CONCENTRATIONS FOR STAGE FIVE SIZE RANGE (1 - 3 MICRONS).

(Number of particles)

		V_1		V_2	
		pen 1	pen 2	pen 3	pen 4
H_1	T_1	F_2Q_2 37,570	F_2Q_1 32,050	F_1Q_2 34,530	F_1Q_1 34,800
	T_3	F_1Q_2 37,610	F_1Q_1 11,940	F_2Q_2 79,900	F_2Q_1 52,290
	T_6	F_1Q_1 33,080	F_2Q_2 32,270	F_2Q_1 28,980	F_1Q_2 25,570
	T_7	F_2Q_1 37,380	F_1Q_2 21,170	F_1Q_1 25,160	F_2Q_2 57,690
H_2	T_2	F_2Q_1 39,930	F_1Q_2 27,730	F_1Q_1 33,670	F_2Q_2 55,970
	T_4	F_1Q_2 16,270	F_1Q_1 16,890	F_2Q_2 15,140	F_2Q_1 24,930
	T_5	F_1Q_1 12,210	F_2Q_2 23,140	F_2Q_1 32,450	F_1Q_2 34,410
	T_8	F_2Q_2 16,150	F_2Q_1 11,750	F_1Q_2 25,150	F_1Q_1 24,600

TABLE C6: ATMOSPHERIC DUST CONCENTRATIONS FOR STAGE SIX SIZE RANGE (0.7 - 2.2 MICRONS).

(Number of particles)

		V_1		V_2	
		pen 1	pen 2	pen 3	pen 4
H_1	T_1	F_2Q_2 23,560	F_2Q_1 22,940	F_1Q_2 26,660	F_1Q_1 19,390
	T_3	F_1Q_2 17,710	F_1Q_1 7,000	F_2Q_2 41,000	F_2Q_1 37,780
	T_6	F_1Q_1 24,520	F_2Q_2 19,470	F_2Q_1 17,620	F_1Q_2 13,860
	T_7	F_2Q_1 16,090	F_1Q_2 13,880	F_1Q_1 14,280	F_2Q_2 30,460
H_2	T_2	F_2Q_1 24,650	F_1Q_2 12,420	F_1Q_1 24,320	F_2Q_2 26,940
	T_4	F_1Q_2 11,720	F_1Q_1 8,640	F_2Q_2 8,990	F_2Q_1 12,670
	T_5	F_1Q_1 7,070	F_2Q_2 15,490	F_2Q_1 17,630	F_1Q_2 21,580
	T_8	F_2Q_2 8,100	F_2Q_1 7,560	F_1Q_2 15,070	F_1Q_1 12,040

TABLE C7: ATMOSPHERIC DUST CONCENTRATIONS FOR LUNG PENETRATION SIZE RANGE (<5 MICRONS).

(Number of particles)

		V_1		V_2	
		pen 1	pen 2	pen 3	pen 4
H_1	T_1	F_2Q_2 146,020	F_2Q_1 105,030	F_1Q_2 106,930	F_1Q_1 114,020
	T_3	F_1Q_2 128,860	F_1Q_1 50,890	F_2Q_2 259,150	F_2Q_1 167,313
	T_6	F_1Q_1 107,420	F_2Q_2 92,200	F_2Q_1 92,410	F_1Q_2 80,930
	T_7	F_2Q_1 112,390	F_1Q_2 77,420	F_1Q_1 86,430	F_2Q_2 191,280
H_2	T_2	F_2Q_1 133,070	F_1Q_2 84,330	F_1Q_1 117,570	F_2Q_2 150,650
	T_4	F_1Q_2 65,650	F_1Q_1 49,670	F_2Q_2 58,990	F_2Q_1 78,360
	T_5	F_1Q_1 45,980	F_2Q_2 83,560	F_2Q_1 97,520	F_1Q_2 126,780
	T_8	F_2Q_2 54,730	F_2Q_1 45,500	F_1Q_2 73,780	F_1Q_1 97,610

TABLE C8: SETTLED DUST.

(mg/hr-cm^2) x 10^2

		V_1		V_2	
		pen 1	pen 2	pen 3	pen 4
H_1	T_1	F_2Q_2 5.28	F_2Q_1 4.42	F_1Q_2 4.63	F_1Q_1 6.64
	T_3	F_1Q_2 10.20	F_1Q_1 11.07	F_2Q_2 1.80	F_2Q_1 4.13
	T_6	F_1Q_1 6.52	F_2Q_2 1.97	F_2Q_1 2.44	F_1Q_2 7.54
	T_7	F_2Q_1 4.04	F_1Q_2 7.78	F_1Q_1 6.18	F_2Q_2 4.84
H_2	T_2	F_2Q_1 2.08	F_1Q_2 4.81	F_1Q_1 4.88	F_2Q_2 3.28
	T_4	F_1Q_2 5.18	F_1Q_1 5.65	F_2Q_2 2.22	F_2Q_1 3.84
	T_5	F_1Q_1 5.83	F_2Q_2 2.46	F_2Q_1 2.83	F_1Q_2 7.64
	T_8	F_2Q_2 2.80	F_2Q_1 2.40	F_1Q_2 3.47	F_1Q_1 7.60

TABLE C9: AVERAGE TEMPERATURES DURING SAMPLING.

(Degrees Fahrenheit)

		V_1		V_2	
		pen 1	pen 2	pen 3	pen 4
H_1	T_1	F_2Q_2 72.0	F_2Q_1 70.3	F_1Q_2 71.7	F_1Q_1 70.0
	T_3	F_1Q_2 74.6	F_1Q_1 72.9	F_2Q_2 73.1	F_2Q_1 69.9
	T_6	F_1Q_1 80.2	F_2Q_2 82.7	F_2Q_1 83.1	F_1Q_2 84.1
	T_7	F_2Q_1 75.9	F_1Q_2 79.0	F_1Q_1 77.9	F_2Q_2 75.9
H_2	T_2	F_2Q_1 66.6	F_1Q_2 70.3	F_1Q_1 69.4	F_2Q_2 71.2
	T_4	F_1Q_2 78.2	F_1Q_1 78.3	F_2Q_2 82.0	F_2Q_1 79.9
	T_5	F_1Q_1 81.2	F_2Q_2 82.2	F_2Q_1 84.3	F_1Q_2 85.4
	T_8	F_2Q_2 76.4	F_2Q_1 76.8	F_1Q_2 83.1	F_1Q_1 78.1

TABLE C10: AVERAGE PIG WEIGHTS.

(Pounds)

		V_1		V_2	
		pen 1	pen 2	pen 3	pen 4
H_1	T_1	F_2Q_2 70.0	F_2Q_1 65.5	F_1Q_2 68.0	F_1Q_1 67.5
	T_3	F_1Q_2 88.5	F_1Q_1 81.8	F_2Q_2 85.0	F_2Q_1 86.2
	T_6	F_1Q_1 117.0	F_2Q_2 111.5	F_2Q_1 114.5	F_1Q_2 113.0
	T_7	F_2Q_1 123.0	F_1Q_2 117.5	F_1Q_1 119.0	F_2Q_2 118.0
H_2	T_2	F_2Q_1 80.0	F_1Q_2 73.5	F_1Q_1 75.5	F_2Q_2 77.5
	T_4	F_1Q_2 100.8	F_1Q_1 94.5	F_2Q_2 100.5	F_2Q_1 98.1
	T_5	F_1Q_1 111.5	F_2Q_2 106.0	F_2Q_1 110.5	F_1Q_2 108.3
	T_8	F_2Q_2 128.8	F_2Q_1 123.7	F_1Q_2 123.5	F_1Q_1 123.5

TABLE C11: AVERAGE RELATIVE HUMIDITIES DURING SAMPLING.

(Percent)

		V_1		V_2	
		pen 1	pen 2	pen 3	pen 4
H_1	T_1	F_2Q_2 30.3	F_2Q_1 22.0	F_1Q_2 39.7	F_1Q_1 22.0
	T_3	F_1Q_2 35.0	F_1Q_1 39.3	F_2Q_2 48.0	F_2Q_1 39.3
	T_6	F_1Q_1 37.0	F_2Q_2 40.0	F_2Q_1 43.0	F_1Q_2 44.7
	T_7	F_2Q_1 43.7	F_1Q_2 46.7	F_1Q_1 46.0	F_2Q_2 52.3
H_2	T_2	F_2Q_1 37.7	F_1Q_2 39.7	F_1Q_1 41.3	F_2Q_2 37.7
	T_4	F_1Q_2 50.0	F_1Q_1 41.7	F_2Q_2 57.7	F_2Q_1 38.7
	T_5	F_1Q_1 40.3	F_2Q_2 43.0	F_2Q_1 55.7	F_1Q_2 43.7
	T_8	F_2Q_2 63.3	F_2Q_1 46.7	F_1Q_2 57.0	F_1Q_1 44.0

APPENDIX D. ANALYSIS OF COVARIANCE APL COMPUTER PROGRAMS.

Data input is via two matrices. The rows of each are the sources of variation. The columns of one matrix (labelled MWX2 and constant for each analysis of covariance) are the covariate cross-products; temperature squared, temperature times weight, weight times temperature, and weight squared. The columns of the other matrix (labelled MWY and a function of particle-size range) are the covariate cross-products combined with the sums of squares of each of the sources of variation.

TABLE D1: APL PROGRAM, ANALYSIS OF COVARIANCE FOR THE COVARIATE WEIGHT.

```
     ∇ COV
[1]    MW← 0 1 1 1 /[2] MWX2
[2]    MW[;(1 2)]←MWY[;(1 3)]
[3]    '         '
[4]    'WORKING MATRIX'
[5]    'COLUMNS                Y(2),XY,X(2)'
[6]    'ROWS                   H[1],R[2],RH[3],(RIH=R+RH)[4]'
[7]    '                       V[5],P[6],PV[7],(PIV=P+PV)[8]'
[8]    '                       HV[9],HP[10],HPV[11],(HPIV=HP+HPV)[12]'
[9]    '                       F[13],Q[14],FQ[15],HF[16],HQ[17],VQ[18]'
[10]   '                       HPQ[19],HVQ[20],(RESIDUAL)[21],TOTAL[22]';MW
[11]   R1←MW[1;]+MW[4;]
[12]   R2←MW[4;]
[13]   R3←MW[5;]+MW[8;]
[14]   R4←MW[8;]
[15]   R5←MW[9;]+MW[12;]
[16]   R6←MW[12;]
[17]   R7←MW[13;]+MW[21;]
[18]   R8←MW[14;]+MW[21;]
[19]   R9←MW[15;]+MW[21;]
[20]   R10←MW[16;]+MW[21;]
[21]   R11←MW[17;]+MW[21;]
[22]   R12←MW[18;]+MW[21;]
[23]   R13←MW[19;]+MW[21;]
[24]   R14←MW[20;]+MW[21;]
[25]   R15←MW[21;]
[26]   '      '
[27]   '---------------------------------------------------------------'
[28]   'MATRIX OF SUM OF SQUARES PLUS THEIR VALID ERROR TERMS'
[29]   'COLUMNS:               SAME AS BEFORE'
[30]   'ROWS:                  R1(1+4) R2(4) R3(5+8) R4(8) R5(9+12)R6(12) R7(13+21) R8(14+21)'
```

TABLE D1: (continued)

```
[31]  '                        R9(15+21)  R10(16+21)  R11(17+21)  R12(18+21) R13(19+21)'
[32]  '                        R14(20+21)  R15(21)'
[33]  MW←⎕← 15 3 ⍴R1,R2,R3,R4,R5,R6,R7,R8,R9,R10,R11,R12,R13,R14,R15
[34]  J←1
[35]  Y← 1 0 0 /[2] MW
[36]  DATA←MW[J;]
[37]  'ROW';J
[38]  X←⎕←(1 1)⍴¯1↑DATA
[39]  '-----------------------'
[40]  I←⎕←⌹X
[41]  '-----------------------'
[42]  'B VALUES'
[43]  B←⎕←I+.×C←(¯1↑(2↑DATA) )
[44]  'SSR      ';SSR←+/(B×C)
[45]  'YSQ      ';DATA[1]
[46]  '         '
[47]  '         '
[48]  'ADJUSTED Y   ';Y[J;]←DATA[1]-SSR
[49]  '         '
[50]  '         '
[51]  J←J+1
[52]  →36×⍳(J≤15)
[53]  →54
[54]  A← 1 0 0 /[2] MW
[55]  A[1;]←Y[1;]-Y[2;]
[56]  A[2;]←Y[2;]
[57]  A[3;]←Y[3;]-Y[4;]
[58]  A[4;]←Y[4;]
[59]  A[5;]←Y[5;]-Y[6;]
[60]  A[6;]←Y[6;]
```

TABLE D1: (continued)

```
[61]  A[7;]←Y[7;]-Y[15;]
[62]  A[8;]←Y[8;]-Y[15;]
[63]  A[9;]←Y[9;]-Y[15;]
[64]  A[10;]←Y[10;]-Y[15;]
[65]  A[11;]←Y[11;]-Y[15;]
[66]  A[12;]←Y[12;]-Y[15;]
[67]  A[13;]←Y[13;]-Y[15;]
[68]  A[14;]←Y[14;]-Y[15;]
[69]  A[15;]←Y[15;]
[70]  'MATRIX OF ADJUSTED SUMS OF SQUARES OF SOURCES FOR THE COVARIATE  WEIGHT'
[71]  'NOTE:   THE USE OF A SINGLE COVARIATE REMOVES 1 OF THE 2 D.F. FROM EACH OF
                 THE TERMS; A[4;](PIV) AND A[6;](HPIV) .  THUS THE TESTS; V AGAINST
                 PIV , AND HV AGAINST HPIV ARE OF DOUBTFUL VALUE.'
[72]  A←⌈A
[73]  ''
[74]  'F VALUES'
[75]  ''
[76]  'H----';A[1;]÷(A[2;]÷6)
[77]  'V----';A[3;]÷(A[4;]÷2)
[78]  'HV---';A[5;]÷(A[6;]÷2)
[79]  'P----';A[7;]÷(A[15;]÷9)
[80]  'Q----';A[8;]÷(A[15;]÷9)
[81]  'PQ---';A[9;]÷(A[15;]÷9)
[82]  'HP---';A[10;]÷(A[15;]÷9)
[83]  'HQ---';A[11;]÷(A[15;]÷9)
[84]  'VQ---';A[12;]÷(A[15;]÷9)
[85]  'HPQ--';A[13;]÷(A[15;]÷9)
[86]  'HVQ--';A[14;]÷(A[15;]÷9)
    ∇
```

TABLE D2: APL PROGRAM, ANALYSIS OF COVARIANCE FOR THE COVARIATE TEMPERATURE.

```
     ∇ COV
[1]    MW← 0 1 1 1 /[2] MWX2
[2]    MW[;(1 2)]←MVY[;(1 3)]
[3]    '         '
[4]    'WORKING MATRIX'
[5]    'COLUMNS              Y(2),XY,X(2)'
[6]    'ROWS                 H[1],R[2],RH[3],(RIH=R+RH)[4]'
[7]    '                     V[5],P[6],PV[7],(PIV=P+PV)[8]'
[8]    '                     HV[9],HP[10],HPV[11],(HPIV=HP+HPV)[12]'
[9]    '                     F[13],Q[14],FQ[15],HF[16],HQ[17],VQ[18]'
[10]   '                     HFQ[19],HVQ[20],(RESIDUAL)[21],TOTAL[22]';MW
[11]   R1←MW[1;]+MW[4;]
[12]   R2←MW[4;]
[13]   R3←MW[5;]+MW[8;]
[14]   R4←MW[8;]
[15]   R5←MW[9;]+MW[12;]
[16]   R6←MW[12;]
[17]   R7←MW[13;]+MW[21;]
[18]   R8←MW[14;]+MW[21;]
[19]   R9←MW[15;]+MW[21;]
[20]   R10←MW[16;]+MW[21;]
[21]   R11←MW[17;]+MW[21;]
[22]   R12←MW[18;]+MW[21;]
[23]   R13←MW[19;]+MW[21;]
[24]   R14←MW[20;]+MW[21;]
[25]   R15←MW[21;]
[26]   '         '
[27]   '-----------------------------------------------------------------'
[28]   'MATRIX OF SUM OF SQUARES PLUS THEIR VALID ERROR TERMS'
[29]   'COLUMNS:             SAME AS BEFORE'
[30]   'ROWS:                R1(1+4) R2(4) R3(5+8) R4(8) R5(9+12)R6(12) R7(13+21) R8(14+21)'
```

TABLE D2: (continued)

```
[31]  '                    R9(15+21)  R10(16+21)  R11(17+21)  R12(18+21) R13(19+21)'
[32]  '                    R14(20+21)  R15(21)'
[33]  MW←⎕← 15 3 ⍴R1,R2,R3,R4,R5,R6,R7,R8,R9,R10,R11,R12,R13,R14,R15
[34]  J←1
[35]  Y← 1 0 0 /[2] MW
[36]  DATA←MW[J;]
[37]  'ROW';J
[38]  X←⎕←(1 1)⍴¯1↑DATA
[39]  '-----------------------'
[40]  I←⎕←⌹X
[41]  '-----------------------'
[42]  'B VALUES'
[43]  B←⎕←I+.×C←(¯1↑(2↑DATA))
[44]  'SSR      ';SSR←+/(B×C)
[45]  'YSQ      ';DATA[1]
[46]  '         '
[47]  '         '
[48]  'ADJUSTED Y   ';Y[J;]←DATA[1]-SSR
[49]  '         '
[50]  '         '
[51]  J←J+1
[52]  →36×⍳(J≤15)
[53]  →54
[54]  A← 1 0 0 /[2] MW
[55]  A[1;]←Y[1;]-Y[2;]
[56]  A[2;]←Y[2;]
[57]  A[3;]←Y[3;]-Y[4;]
[58]  A[4;]←Y[4;]
[59]  A[5;]←Y[5;]-Y[6;]
[60]  A[6;]←Y[6;]
```

TABLE D2: (continued)

```
[61]  A[7;]←Y[7;]-Y[15;]
[62]  A[8;]←Y[8;]-Y[15;]
[63]  A[9;]←Y[9;]-Y[15;]
[64]  A[10;]←Y[10;]-Y[15;]
[65]  A[11;]←Y[11;]-Y[15;]
[66]  A[12;]←Y[12;]-Y[15;]
[67]  A[13;]←Y[13;]-Y[15;]
[68]  A[14;]←Y[14;]-Y[15;]
[69]  A[15;]←Y[15;]
[70]  'MATRIX OF ADJUSTED SUMS OF SQUARES OF SOURCES FOR THE COVARIATE TEMPERATURE'
[71]  'NOTE:   THE USE OF A SINGLE COVARIATE REMOVES 1 OF THE 2 D.F. FROM EACH OF
                 THE TERMS; A[4;](PIV) AND A[6;](HPIV).  THUS THE TESTS; V AGAINST
                 PIV , AND HV AGAINST HPIV ARE OF DOUBTFUL VALUE.'
[72]  A←⌈←A
[73]  ''
[74]  'F VALUES'
[75]  ''
[76]  'H----';A[1;]÷(A[2;]÷6)
[77]  'V----';A[3;]÷(A[4;]÷2)
[78]  'HV---';A[5;]÷(A[6;]÷2)
[79]  'P----';A[7;]÷(A[15;]÷9)
[80]  'Q----';A[8;]÷(A[15;]÷9)
[81]  'PQ---';A[9;]÷(A[15;]÷9)
[82]  'HP---';A[10;]÷(A[15;]÷9)
[83]  'HQ---';A[11;]÷(A[15;]÷9)
[84]  'VQ---';A[12;]÷(A[15;]÷9)
[85]  'HPQ--';A[13;]÷(A[15;]÷9)
[86]  'HVQ--';A[14;]÷(A[15;]÷9)
    ∇
```

TABLE D3: APL PROGRAM, ANALYSIS OF COVARIANCE FOR THE COVARIATES WEIGHT AND TEMPERATURE.

```
     ∇ COV
[1]    MW← 0 0 0 1 1 1 1\[2] MWX2
[2]    MW[;(1 2 3)]←MWY[;(1 2 3)]
[3]    '          '
[4]    'WORKING MATRIX'
[5]    'COLUMNS              Y(2),XY,X(2)'
[6]    'ROWS                 H[1],R[2],RH[3],(RIH=R+RH)[4]'
[7]    '                     V[5],P[6],PV[7],(PIV=P+PV)[8]'
[8]    '                     HV[9],HP[10],HPV[11],(HPIV=HP+HPV)[12]'
[9]    '                     F[13],Q[14],FQ[15],HF[16],HQ[17],VQ[18]'
[10]   '                     HFQ[19],HVQ[20],(RESIDUAL)[21],TOTAL[22]';MW
[11]   R1←MW[1;]+MW[4;]
[12]   R2←MW[4;]
[13]   R3←MW[5;]+MW[8;]
[14]   R4←MW[8;]
[15]   R5←MW[9;]+MW[12;]
[16]   R6←MW[12;]
[17]   R7←MW[13;]+MW[21;]
[18]   R8←MW[14;]+MW[21;]
[19]   R9←MW[15;]+MW[21;]
[20]   R10←MW[16;]+MW[21;]
[21]   R11←MW[17;]+MW[21;]
[22]   R12←MW[18;]+MW[21;]
[23]   R13←MW[19;]+MW[21;]
[24]   R14←MW[20;]+MW[21;]
[25]   R15←MW[21;]
[26]   '          '
[27]   '-------------------------------------------------------------'
[28]   'MATRIX OF SUM OF SQUARES PLUS THEIR VALID ERROR TERMS'
[29]   'COLUMNS:             SAME AS BEFORE'
[30]   'ROWS:                R1(1+4) R2(4) R3(5+8) R4(8) R5(9+12)R6(12) R7(13+21) R8(14+21)'
```

TABLE D3: (continued)

```
[31]  '                      R9(15+21) R10(16+21) R11(17+21) R12(18+21) R13(19+21)'
[32]  '                      R14(20+21) R15(21)'
[33]  MW←⎕← 15 7 ⍴R1,R2,R3,R4,R5,R6,R7,R8,R9,R10,R11,R12,R13,R14,R15
[34]  J←1
[35]  Y← 1 0 0 0 0 0 0 /[2] MW
[36]  DATA←MW[J;]
[37]  'ROW';J
[38]  X←⎕←(2 2)⍴¯4↑DATA
[39]  '-----------------------'
[40]  I←⎕←⌹X
[41]  '-----------------------'
[42]  'B VALUES'
[43]  B←⎕←I+.×C←(¯2↑(3↑DATA))
[44]  'SSR        ';SSR←+/(B×C)
[45]  'YSQ        ';DATA[1]
[46]  '           '
[47]  '           '
[48]  'ADJUSTED Y     ';Y[J;]←DATA[1]-SSR
[49]  '           '
[50]  '           '
[51]  J←J+1
[52]  →36×⍳(J≤15)
[53]  →54
[54]  A← 1 0 0 0 0 0 0 /[2] MW
[55]  A[1;]←Y[1;]-Y[2;]
[56]  A[2;]←Y[2;]
[57]  A[3;]←Y[3;]-Y[4;]
[58]  A[4;]←Y[4;]
[59]  A[5;]←Y[5;]-Y[6;]
[60]  A[6;]←Y[6;]
```

TABLE D3: (continued)

```
[61]  A[7;]←Y[7;]-Y[15;]
[62]  A[8;]←Y[8;]-Y[15;]
[63]  A[9;]←Y[9;]-Y[15;]
[64]  A[10;]←Y[10;]-Y[15;]
[65]  A[11;]←Y[11;]-Y[15;]
[66]  A[12;]←Y[12;]-Y[15;]
[67]  A[13;]←Y[13;]-Y[15;]
[68]  A[14;]←Y[14;]-Y[15;]
[69]  A[15;]←Y[15;]
[70]  'MATRIX OF ADJUSTED SUMS OF SQUARES OF SOURCES FOR THE COVARIATES.
           TEMPERATURE AND WEIGHT.'
[71]  'NOTE:   THE A[4;](PIV) AND A[6;](HPIV) TERMS ARE MEANINGLESS
                   SINCE THE 2 DF. OF EACH WERE REMOVED BY USING THE 2
                   COVARIATES.  THIS LEFT AN ADJUSTED Y OF ZERO, PLUS OR
                   MINUS ROUNDING.  THUS, V AGAINST PIV AND HV AGAINST HPIV
                   ARE MEANINGLESS TESTS.'
[72]  A←⎕←A
[73]  ''
[74]  'F VALUES'
[75]  ''
[76]  'H----';A[1;]÷(A[2;]÷6)
[77]  'V----';A[3;]÷(A[4;]÷2)
[78]  'HV---';A[5;]÷(A[6;]÷2)
[79]  'F----';A[7;]÷(A[15;]÷9)
[80]  'Q----';A[8;]÷(A[15;]÷9)
[81]  'FQ---';A[9;]÷(A[15;]÷9)
[82]  'HF---';A[10;]÷(A[15;]÷9)
[83]  'HQ---';A[11;]÷(A[15;]÷9)
[84]  'VQ---';A[12;]÷(A[15;]÷9)
[85]  'HFQ--';A[13;]÷(A[15;]÷9)
[86]  'HVQ--';A[14;]÷(A[15;]÷9)
    ∇
```

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APPENDIX E. ANALYSIS OF COVARIANCE RESULTS.

TABLE E1: ANALYSIS OF COVARIANCE, PARTICLE-SIZE RANGE ONE
(11 - 16 MICRONS), COVARIATE TEMPERATURE.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	673,000,000	4.25
ERROR (1) (Rows / H)	6	158,000,000	
V (Volume)	1	166,000,000	9.00
ERROR (2) (Pens / V)	2	18,400,000	
H x V	1	52,700,000	42.66*
ERROR (3) (H x Pens / V)	2	1,240,000	
F (Feed)	1	18,300,000	<1.00
Q (Air Flow Rate)	1	2,440,000	<1.00
F x Q	1	29,650,000	<1.00
H x F	1	21,000,000	<1.00
H x Q	1	231,000,000	4.30
V x Q	1	3,470,000	<1.00
H x F x Q	1	291,000	<1.00
H x V x Q	1	21,900,000	<1.00
ERROR (4) (Residual)	9	53,740,000	
TOTAL	30		

* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE E2: ANALYSIS OF COVARIANCE, PARTICLE-SIZE RANGE TWO (7 - 9 MICRONS), COVARIATE TEMPERATURE.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	213,000,000	2.31
ERROR (1) (Rows / H)	6	92,400,000	
V (Volume)	1	178,000,000	4.28
ERROR (2) (Pens / V)	2	41,600,000	
H x V	1	144,000,000	250.60**
ERROR (3) (H x Pens / V)	2	573,000	
F (Feed)	1	3,440,000	<1.00
Q (Air Flow Rate)	1	146,000,000	15.86**
F x Q	1	8,890,000	<1.00
H x F	1	17,100,000	1.85
H x Q	1	170,000,000	18.40**
V x Q	1	1,860,000	<1.00
H x F x Q	1	28,700,000	3.12
H x V x Q	1	5,010	<1.00
ERROR (4) (Residual)	9	9,218,000	
TOTAL	30		

* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE E3: ANALYSIS OF COVARIANCE, PARTICLE-SIZE RANGE THREE (3 - 5 MICRONS), COVARIATE TEMPERATURE.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	291,000,000	6.43*
ERROR (1) (Rows / H)	6	45,110,000	
V (Volume)	1	549,000,000	15.74
ERROR (2) (Pens / V)	2	34,900,000	
H x V	1	105,000,000	73.36*
ERROR (3) (H x Pens / V)	2	1,430,000	
F (Feed)	1	50,800,000	1.68
Q (Air Flow Rate)	1	188,000,999	6.21*
F x Q	1	8,500,000	<1.00
H x F	1	140,000,000	4.63
H x Q	1	133,000,000	4.40
V x Q	1	1,690,000	<1.00
H x F x Q	1	78,640,000	2.60
H x V x Q	1	399,000	<1.00
ERROR (4) (Residual)		30,300,000	
TOTAL	30		

* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE E4: ANALYSIS OF COVARIANCE, PARTICLE-SIZE RANGE FOUR (1.8 - 3.8 MICRONS), COVARIATE TEMPERATURE.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	466,000,000	2.31
ERROR (1) (Rows / H)	6	201,600,000	
V (Volume)	1	825,000,000	35.68*
ERROR (2) (Pens / V)	2	23,100,000	
H x V	1	202,000,000	145.40**
ERROR (3) (H x Pens / V)	2	1,390,000	
F (Feed)	1	270,000,000	2.27
Q (Air Flow Rate)	1	208,000,000	1.75
F x Q	1	39,500,000	<1.00
H x F	1	465,000,000	3.92
H x Q	1	145,000,000	1.22
V x Q	1	28,700,000	<1.00
H x F x Q	1	295,000,000	2.49
H x V x Q	1	2,530,000	<1.00
ERROR (4) (Residual)		118,600,000	
TOTAL	30		

* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE E5: ANALYSIS OF COVARIANCE, PARTICLE-SIZE RANGE FIVE (1 - 3 MICRONS), COVARIATE TEMPERATURE.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	583,000,000	4.56
ERROR (1) (Rows / H)	6	128,000,000	
V (Volume)	1	997,000,000	65.28*
ERROR (2) (Pens / V)	2	15,300,000	
H x V	1	182,600,000	146.40**
ERROR (3) (H x Pens / V)	2	1,250,000	
F (Feed)	1	295,000,000	3.11
Q (Air Flow Rate)	1	393,000,000	4.14
F x Q	1	2,595,000	<1.00
H x F	1	272,000,000	2.86
H x Q	1	71,600,000	<1.00
V x Q	1	103,000,000	1.09
H x F x Q	1	131,000,000	1.38
H x V x Q	1	4,080,000	<1.00
ERROR (4) (Residual)	9	94,840,000	
TOTAL	30		

* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE E6: ANALYSIS OF COVARIANCE, PARTICLE-SIZE RANGE SIX (0.7 - 2.2 MICRONS), COVARIATE TEMPERATURE.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	261,000,000	6.83*
ERROR (1) (Rows / H)	6	38,160,000	
V (Volume)	1	242,000,000	31.96*
ERROR (2) (Pens / V)	2	7,580,000	
H x V	1	11,800,000	456.97**
ERROR (3) (H x Pens / V)		25,800	
F (Feed)	1	5,220,000	<1.00
Q (Air Flow Rate)	1	332,500,000	12.62**
F x Q	1	64,700,000	2.46
H x F	1	66,800,000	2.54
H x Q	1	6,290,000	<1.00
V x Q	1	25,800,000	<1.00
H x F x Q	1	38,200,000	1.45
H x V x Q	1	50,400,000	1.91
ERROR (4) (Residual)	9	26,340,000	
TOTAL	30		

* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE E7: ANALYSIS OF COVARIANCE, LUNG PENETRATION PARTICLE-SIZE (5 MICRONS), COVARIATE TEMPERATURE.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	6,230,000,000	5.23
ERROR (1) (Rows / H)	6	1,189,000,000	
V (Volume)	1	9,860,000,000	32.66*
ERROR (2) (Pens / V)	2	302,000,000	
H x V	1	1,710,000,000	154.40**
ERROR (3) (H x Pens / V)	2	11,100,000	
F (Feed)	1	1,850,000,000	2.52
Q (Air Flow Rate)	1	4,380,000,000	5.95*
F x Q	1	110,000	<1.00
H x F	1	3,370,000,000	4.58
H x Q	1	1,190,000,000	1.62
V x Q	1	477,000,000	<1.00
H x F x Q	1	1,910,000,000	2.59
H x V x Q	1	47,400,000	<1.00
ERROR (4) (Residual)	9	735,700,000	
TOTAL	30		

* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE E8: ANALYSIS OF COVARIANCE, PARTICLE-SIZE RANGE ONE (11 - 16 MICRONS), COVARIATE WEIGHT.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	749,000,000	7.94*
ERROR (1) (Rows / H)	6	94,300,000	
V (Volume)	1	112,000,000	12.32
ERROR (2) (Pens / V)	2	9,070,000	
H x V	1	186,000,000	72.54*
ERROR (3) (H x Pens / V)	2	2,570,000	
F (Feed)	1	6,610,000	<1.00
Q (Air Flow Rate)	1	28,700,000	<1.00
F x Q	1	12,200,000	<1.00
H x F	1	2,680,000	<1.00
H x Q	1	187,000,000	3.50
V x Q	1	3,580,000	<1.00
H x F x Q	1	373,000	<1.00
H x V x Q	1	8,400,000	<1.00
ERROR (4) (Residual)	9	53,470,000	
TOTAL	30		

* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE E9: ANALYSIS OF COVARIANCE, PARTICLE-SIZE RANGE TWO (7 - 9 MICRONS), COVARIATE WEIGHT.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	231,000,000	4.97
ERROR (1) (Rows / H)	6	46,500,000	
V (Volume)	1	145,000,000	54.51*
ERROR (2) (Pens / V)	2	2,660,000	
H x V	1	104,000,000	1027.00**
ERROR (3) (H x Pens / V)	2	102,000	
F (Feed)	1	2,190,000	<1.00
Q (Air Flow Rate)	1	171,000,000	14.75**
F x Q	1	51,540,000	4.45
H x F	1	37,400,000	3.23
H x Q	1	193,000,000	16.63**
V x Q	1	1,670,000	<1.00
H x F x Q	1	33,000,000	2.85
H x V x Q	1	19,900,000	1.72
ERROR (4) (Residual)	9	11,580,000	
TOTAL	30		

* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE E10: ANALYSIS OF COVARIANCE, PARTICLE-SIZE RANGE THREE (3 - 5 MICRONS), COVARIATE WEIGHT.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	348,000,000	5.78
ERROR (1) (Rows / H)	6	60,200,000	
V (Volume)	1	382,000,000	9.94
ERROR (2) (Pens / V)	2	38,400,000	
H x V	1	51,800,000	102.80**
ERROR (3) (H x Pens / V)	2	504,000	
F (Feed)	1	59,500,000	1.65
Q (Air Flow Rate)	1	175,000,000	4.84
F x Q	1	53,800,000	1.49
H x F	1	129,000,000	3.58
H x Q	1	148,000,000	4.09
V x Q	1	1,230,000	<1.00
H x F x Q	1	69,900,000	1.93
H x V x Q	1	29,900,000	<1.00
ERROR (4) (Residual)	9	36,170,000	
TOTAL	30		

* Significant at the 5% probability level.

** Significant at the 1% probability level.

TABLE E11: ANALYSIS OF COVARIANCE, PARTICLE-SIZE RANGE FOUR (1.8 - 3.8 MICRONS), COVARIATE WEIGHT.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	579,000,000	2.32
ERROR (1) (Rows / H)	6	249,700,000	
V (Volume)	1	622,000,000	9.22
ERROR (2) (Pens / V)	2	67,450,000	
H x V	1	84,700,000	260.60**
ERROR (3) (H x Pens / V)	2	325,000	
F (Feed)	1	239,000,000	1.93
Q (Air Flow Rate)	1	229,000,000	1.85
F x Q	1	107,000,000	<1.00
H x F	1	343,000,000	2.77
H x Q	1	156,000,000	1.26
V x Q	1	26,700,000	<1.00
H x F x Q	1	257,000,000	2.07
H x V x Q	1	36,500,000	<1.00
ERROR (4) (Residual)	9	123,800,000	
TOTAL	30		

* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE E12: ANALYSIS OF COVARIANCE, PARTICLE-SIZE RANGE FIVE (1 - 3 MICRONS), COVARIATE WEIGHT.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	707,000,000	4.01
ERROR (1) (Rows / H)	6	176,400,000	
V (Volume)	1	1,050,000,000	20.68*
ERROR (2) (Pens / V)	2	50,600,000	
H x V	1	66,600,000	233.80**
ERROR (3) (H x Pens / V)	2	235,000	
F (Feed)	1	253,000,000	2.29
Q (Air Flow Rate)	1	258,000,000	2.32
F x Q	1	47,500,000	<1.00
H x F	1	322,000,000	2.91
H x Q	1	113,000,000	1.02
V x Q	1	98,200,000	<1.00
H x F x Q	1	134,000,000	1.21
H x V x Q	1	49,600,000	<1.00
ERROR (4) (Residual)	9	110,800,000	
TOTAL	30		

* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE E13: ANALYSIS OF COVARIANCE, PARTICLE-SIZE RANGE SIX (0.7 - 2.2 MICRONS), COVARIATE WEIGHT.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	290,000,000	8.16*
ERROR (1) (Rows / H)	6	35,600,000	
V (Volume)	1	324,000,000	77.07*
ERROR (2) (Pens / V)	2	4,210,000	
H x V	1	566,000	5.38
ERROR (3) (H x Pens / V)	2	105,000	
F (Feed)	1	57,800,000	<1.00
Q (Air Flow Rate)	1	36,700,000	<1.00
F x Q	1	2,570,000	<1.00
H x F	1	111,000,000	1.78
H x Q	1	20,640,000	<1.00
V x Q	1	20,600,000	<1.00
H x F x Q	1	27,700,000	<1.00
H x V x Q	1	11,000,000	<1.00
ERROR (4) (Residual)	9	62,080,000	
TOTAL	30		

* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE E14: ANALYSIS OF COVARIANCE, LUNG PENETRATION PARTICLE-SIZE (<5 MICRONS), COVARIATE WEIGHT.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	7,460,000,000	4.58
ERROR (1) (Rows / H)	6	1,626,000,000	
V (Volume)	1	8,996,000,000	16.18
ERROR (2) (Pens / V)	2	555,900,000	
H x V	1	641,500,000	275.20**
ERROR (3) (H x Pens / V)	2	2,300,000	
F (Feed)	1	2,180,000,000	2.29
Q (Air Flow Rate)	1	2,550,000,000	2.67
F x Q	1	684,000,000	<1.00
H x F	1	3,410,000,000	3.57
H x Q	1	1,590,000,000	1.66
V x Q	1	429,000,000	<1.00
H x F x Q	1	1,700,000,000	1.78
H x V x Q	1	478,000,000	<1.00
ERROR (4) (Residual)	9	953,700,000	
TOTAL	30		

* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE E15: ANALYSIS OF COVARIANCE, SETTLED DUST, COVARIATE WEIGHT.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	15.25	7.67*
ERROR (1) (Rows / H)	6	1.987	
V (Volume)	1	2.28	<1.00
ERROR (2) (Pens / V)	2	0.915	
H x V	1	5.02	464.20**
ERROR (3) (H x Pens / V)	2	0.0108	
F (Feed)	1	35.0	19.76**
Q (Air Flow Rate)	1	0.855	<1.00
F x Q	1	0.052	<1.00
H x F	1	3.53	1.99
H x Q	1	0.00046	<1.00
V x Q	1	0.11	<1.00
H x F x Q	1	0.93	<1.00
H x V x Q	1	0.0096	<1.00
ERROR (4) (Residual)	9	1.77	
TOTAL	30		

* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE E16: ANALYSIS OF COVARIANCE, PARTICLE-SIZE RANGE ONE
(11 - 16 MICRONS), COVARIATES TEMPERATURE AND WEIGHT.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	687,700,000	8.00*
ERROR (1) (Rows / H)	6	86,000,000	
V (Volume)	1	no test	
ERROR (2) (Pens / V)	2	zero	
H x V	1	no test	
ERROR (3) (H x Pens / V)	2	zero	
F (Feed)	1	5,980,000	<1.00
Q (Air Flow Rate)	1	4,440,000	<1.00
F x Q	1	11,200,000	<1.00
H x F	1	3,540,000	<1.00
H x Q	1	183,100,000	3.05
V x Q	1	3,660,000	<1.00
H x F x Q	1	1,020	<1.00
H x V x Q		8,120,000	<1.00
ERROR (4) (Residual)	8	60,040,000	
TOTAL	29		

* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE E17: ANALYSIS OF COVARIANCE, PARTICLE-SIZE RANGE TWO (7 - 9 MICRONS), COVARIATES TEMPERATURE AND WEIGHT.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	219,900,000	4.79
ERROR (1) (Rows / H)	6	45,830,000	
V (Volume)	1	no test	
ERROR (2) (Pens / V)	2	zero	
H x V	1	no test	
ERROR (3) (H x Pens / V)	2	zero	
F (Feed)	1	4,069,000	<1.00
Q (Air Flow Rate)	1	121,000,000	11.80**
F x Q	1	8,590,000	<1.00
H x F	1	12,300,000	1.19
H x Q	1	155,000,000	15.12**
V x Q	1	1,920,000	<1.00
H x F x Q	1	28,200,000	2.75
H x V x Q	1	291,000	<1.00
ERROR (4) (Residual)	8	10,280,000	
TOTAL	29		

* Significant at the 5% probability level.

** Significant at the 1% probability level.

TABLE E18: ANALYSIS OF COVARIANCE, PARTICLE-SIZE RANGE THREE (3 - 5 MICRONS), COVARIATES TEMPERATURE AND WEIGHT.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	292,600,000	7.18*
ERROR (1) (Rows / H)	6	40,700,000	
V (Volume)	1	no test	
ERROR (2) (Pens / V)	2	zero	
H x V	1	no test	
ERROR (3) (H x Pens / V)	2	zero	
F (Feed)	1	46,200,000	1.37
Q (Air Flow Rate)	1	180,000,000	5.34*
F x Q	1	1,950,000	<1.00
H x F	1	49,800,000	1.48
H x Q	1	103,000,000	3.06
V x Q	1	1,590,000	<1.00
H x F x Q	1	58,800,000	1.74
H x V x Q	1	168,000	<1.00
ERROR (4) (Residual)	8	33,750,000	
TOTAL	29		

* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE E19: ANALYSIS OF COVARIANCE, PARTICLE-SIZE RANGE FOUR (1.8 - 3.8 MICRONS), COVARIATES TEMPERATURE AND WEIGHT.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	461,000,000	2.39
ERROR (1) (Rows / H)	6	192,800,000	
V (Volume)	1	no test	
ERROR (2) (Pens / V)	2	zero	
H x V	1	no test	
ERROR (3) (H x Pens / V)	2	zero	
F (Feed)	1	211,000,000	1.59
Q (Air Flow Rate)	1	201,000,000	1.51
F x Q	1	16,000,000	<1.00
H x F	1	186,700,000	1.40
H x Q	1	111,000,000	<1.00
V x Q	1	28,200,000	<1.00
H x F x Q	1	235,000,000	1.77
H x V x Q	1	67,300	<1.00
ERROR (4) (Residual)	8	133,000,000	
TOTAL	29		

* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE E20: ANALYSIS OF COVARIANCE, PARTICLE-SIZE RANGE FIVE (1 - 3 MICRONS), COVARIATES TEMPERATURE AND WEIGHT.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	584,000,000	4.57
ERROR (1) (Rows / H)	6	127,700,000	
V (Volume)	1	no test	
ERROR (2) (Pens / V)	2	zero	
H x V	1	no test	
ERROR (3) (H x Pens / V)	2	zero	
F (Feed)	1	208,000,000	1.95
Q (Air Flow Rate)	1	352,000,000	3.31
F x Q	1	2,820,000	<1.00
H x F	1	122,000,000	1.14
H x Q	1	58,800,000	<1.00
V x Q	1	103,000,000	<1.00
H x F x Q	1	109,000,000	1.02
H x V x Q	1	4,120,000	<1.00
ERROR (4) (Residual)	8	106,600,000	
TOTAL	29		

* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE E21: ANALYSIS OF COVARIANCE, PARTICLE-SIZE RANGE SIX
(0.7 - 2.2 MICRONS), COVARIATES TEMPERATURE AND WEIGHT.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	264,000,000	8.44*
ERROR (1) (Rows / H)	6	31,220,000	
V (Volume)	1	no test	
ERROR (2) (Pens / V)	2	zero	
H x V	1	no test	
ERROR (3) (H x Pens / V)	2	zero	
F (Feed)	1	28,660,000	1.14
Q (Air Flow Rate)	1	368,700,000	14.72**
F x Q	1	101,000,000	4.05
H x F	1	1,850,000	<1.00
H x Q	1	40,300	<1.00
V x Q	1	24,200,000	<1.00
H x F x Q	1	12,700,000	<1.00
H x V x Q	1	86,000,000	3.43
ERROR (4) (Residual)	8	25,040,000	
TOTAL	29		

* Significant at the 5% probability level.
** Significant at the 1% probability level.

TABLE E22: ANALYSIS OF COVARIANCE, LUNG PENETRATION PARTICLE-SIZE (<5 MICRONS), COVARIATES TEMPERATURE AND WEIGHT.

Sources of Variation	Degrees of Freedom	Mean Squares	F-Values
H (Humidity)	1	6,240,000,000	5.27
ERROR (1) (Rows / H)	6	1,184,000,000	
V (Volume)	1	no test	
ERROR (2) (Pens / V)	2	zero	
H x V	1	no test	
ERROR (3) (H x Pens / V)	2	zero	
F (Feed)	1	1,689,000,000	2.07
Q (Air Flow Rate)	1	4,300,000,000	5.27
F x Q	1	39,940,000	<1.00
H x F	1	1,098,000,000	1.35
H x Q	1	815,500,000	1.00
V x Q	1	465,000,000	<1.00
H x F x Q	1	1,370,000,000	1.68
H x V x Q	1	131,000,000	<1.00
ERROR (4) (Residual)	8	814,600,000	
TOTAL	29		

* Significant at the 5% probability level.
** Significant at the 1% probability level.